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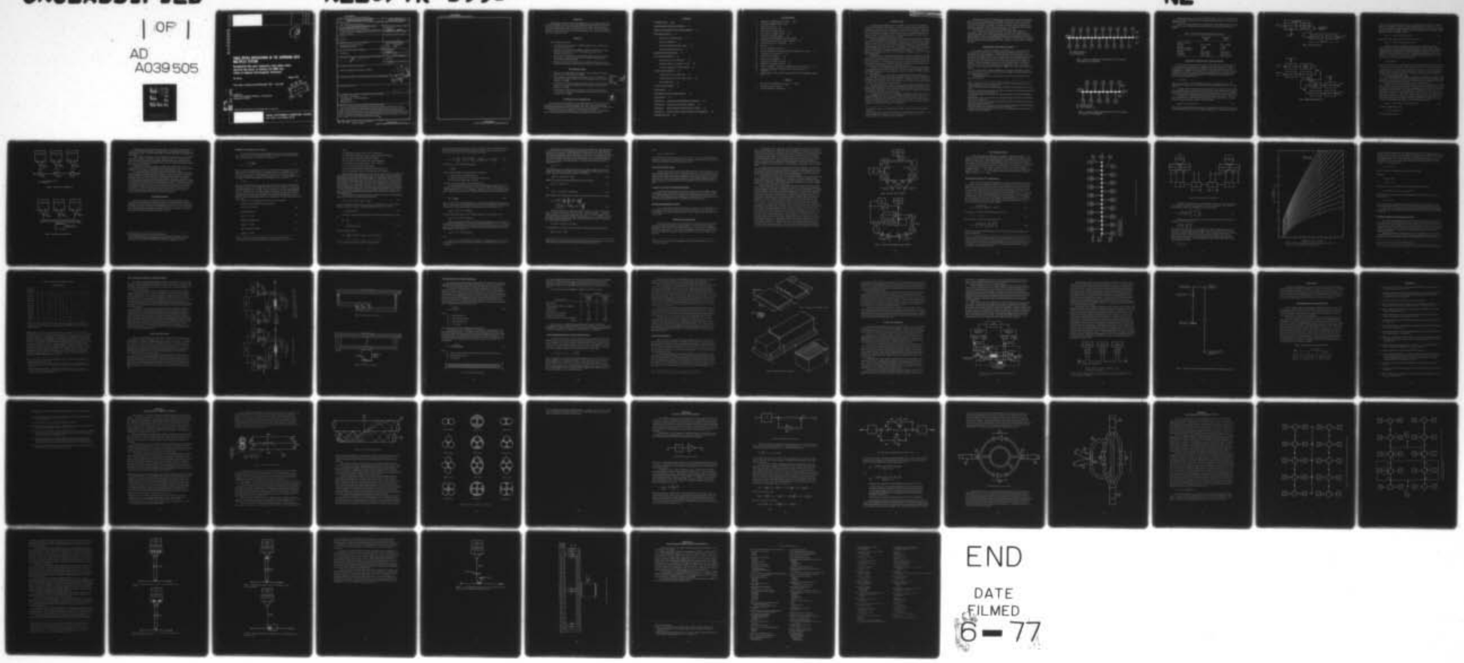

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FIBER OPTICS APPLICATIONS IN THE SHIPBOARD DATA MULTIPLEX SYSTEM

Developmental fiber optic components could replace coaxial electrical data busses, to immunize the SDMS from effects of shipboard electromagnetic interference

DE Altman

August 1976

Final report covering the period November 1975 – June 1976

Prepared for
NAVAL SEA SYSTEMS COMMAND – NAVSEA 034
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For a nominal size Shipboard Data Multiplex System (eight area multiplexers) using a passive tee coupler configuration, the connector and coupler excess losses for each coupler must total no more than 1.8 dB, which appears to be well within the state of the art. For a maximum size system (sixteen area multiplexers) the per coupler losses must be reduced to about 0.5 dB or less, which probably can be achieved given sufficient development effort. Two other devices, the passive star coupler and the fail-safe active tee coupler, also appear to have development potential for use in both nominal and maximum size systems.

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OBJECTIVE

Investigate the application of fiber optics technology to the Shipboard Data Multiplex System (SDMS) on the basis that (1) the SDMS-to-fiber-optic interface will occur at the connectors of the major system components and (2) no change in the structure or operation of SDMS will be required to accommodate fiber optics. (This report considers conversion of the primary busses to fiber optics; conversion of the secondary busses is the subject of a subsequent report.)

RESULTS

The investigation shows that

1. The operation of the nominal size SDMS is possible with use of the passive tee coupler configuration.
2. Operation of the maximum size SDMS is possible in the passive tee configuration if the sum of the connector and coupler excess losses can be reduced to 0.6 dB or less.
3. On the basis of a small amount of published experimental data, reduction of these losses to the required level can reasonably be anticipated, given the necessary development effort.
4. Both the passive star and fail-safe active tee coupler configurations can be developed into satisfactory alternatives to the passive tee coupler configurations.

RECOMMENDATIONS

1. Develop a nine-coupler passive tee bus and evaluate it against the electrical primary busses of the nominal size SDMS.
2. From experience gained during this development, assess the feasibility of achieving the 0.6 dB per coupler excess loss requirement of the 17-coupler maximum size SDMS.
3. If meeting the 0.6 dB per coupler goal appears feasible, develop the required couplers, then assemble and evaluate the 17-coupler bus for use with the maximum size SDMS.
4. If meeting the 0.6 dB per coupler goal does not appear feasible, develop a 17-tap multifiber trunk-type star coupler bus, and evaluate it for use with the maximum size SDMS.

ADMINISTRATIVE INFORMATION

This is a final report of work done in the period November 1975 to June 1976 by the author, a member of the EO/Optics Division (Code 2530), under tasking from the Command Systems Program Office (Code 1200). The work was sponsored by NAVSEA 034 under Program Element 62721N, Project F21224, Task Area SF21224401.

The author expresses his appreciation to DJ Albares, HF Taylor, and EA Howard for their many helpful suggestions offered during the preparation of this report.

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INTRODUCTION

The Shipboard Data Multiplex System (SDMS) is a general purpose information transfer system intended to take the place of most of the point-to-point cabling and associated hardware presently used for information transfer aboard naval ships.[1,2] This new system uses frequency and time multiplexing of a two-level set of redundant interconnections to provide higher reliability and survivability with lower weight than present point-to-point systems. It is potentially capable of distributing throughout a ship all forms of periodic and aperiodic signals, either analog or digital.

Two-level multiplexing, wherein user access is provided through remote multiplexers which transfer information to area multiplexers and thence to a common data bus, allows many access points to be serviced without the attenuation that would result from separate connections to a common data bus. The first stage of multiplexing, consisting primarily of pulse coding in the remote multiplexers, is followed by time multiplex transmission to the area multiplexers at base band. Each area multiplexer serves up to eight remote multiplexers on a direct basis. Each dual redundant remote multiplexer is connected to two adjacent area multiplexers as well as to its associated area multiplexer to provide increased system survivability.

SDMS provides for interchange of information between area multiplexers by both time-division and frequency-division multiplexing over a fivefold redundant data bus, under the control of traffic control units. Since the five data busses can be used independently and four of the five carrier frequencies can be used for message transmission, as many as 20 separate messages can be transmitted at any given instant. The five data busses interconnecting the area multiplexers are termed primary data busses.

As many as 16 area multiplexers per system can be used to support information transfer requirements for ships of various sizes. This study considers only the "maximum size" SDMS, consisting of 16 area multiplexers, and the "nominal size" SDMS, consisting of 8 area multiplexers.

Operation of such a system in the electromagnetically noisy environment of a typical Navy ship can result in interference problems. Primarily because the braided outer conductor of the commonly used coaxial cable is not a continuous surface, a fraction of any noise voltage difference on the outside of the braid also appears on the inside and thus is introduced in series with the transmitted signal.

The rapidly developing technique of data transmission through optical fibers completely avoids this problem, since the optical transmission medium is an insulator. Use of the fiber optic transmission method, along with adequate shielding of the associated electronics modules and filtering of necessary power leads where they penetrate this shielding, can reduce the interference to any desired level.

The objective of this study is to investigate the application of fiber optics technology to SDMS on the basis that (1) the SDMS-to-fiber-optics interface will occur at the connectors of the major system components, and (2) no changes in the structure or operation of SDMS will be required to accommodate fiber optics. This report considers conversion of the primary busses to fiber optics; conversion of the secondary busses is the subject of a companion NELC report to be published.[3]

---

[1] Contract Number N0024-74-C-1200, Shipboard Data Multiplex System Advanced Development Model, 28 June 1974

[2] Autonetics Division, Rockwell International, Preliminary Technical Manual, Operation and Maintenance Instructions, Shipboard Data Multiplex System, Advanced Development Model, 31 August 1975

[3] NELC technical report to be published. Author: JR Campbell

This study proceeds first to determine the maximum bus attenuation that present fiber optic transceiver technology and the SDMS error probability requirement will allow, then uses this information to determine the degree to which tee and star coupler fiber optic replacement busses are feasible. A number of advanced coupler configurations are discussed in connection with the appropriate bus type. A preferred fiber optic configuration is recommended as a replacement for the SDMS primary busses.

To the reader who is unfamiliar with fiber optics, the writer would like to recommend, out of the large volume of literature in the field, an excellent review of fiber optics by Miller et al[4] and a helpful discussion of fiber optic communications link design by Wittke.[5] Also, early investigation of fiber optics for data bus use at NELC is given in reports by Taylor,[6] Howard and Marcus,[7] Taylor et al,[8] and Altman.[9] In addition to these, a comparison of the performance of the tee and star couplers is given by Hudson and Thiel.[10]

SDMS PRIMARY BUS SPECIFICATIONS[1,2,11]

Interconnection between the SDMS area multiplexers is by means of five independent coaxial cable data busses. In the maximum size SDMS, each bus serves the complement of 16 area multiplexers, a traffic control unit, and a maintenance unit. In the nominal size SDMS, each bus serves the complement of 8 area multiplexers, along with the traffic control and maintenance units. Figures 1 and 2 show the interconnection arrangement on one of the five busses, for the maximum and nominal size SDMS, respectively. Each area multiplexer consists of a pair of redundant halves. Each half is connected to each of the five primary busses by separate stubs. Thus each of the five busses has a total of 34 taps in the maximum size SDMS and 18 taps in the nominal size system.

To effect frequency division multiplexing, five frequency modulated carriers are injected on each bus, at 45.0, 53.4, 61.8, 70.2, and 78.6 MHz. Each carrier handles data at 1.2 megabits per second.

The SDMS design calls for a bit error rate of 10^{-6} errors per bit prior to error correction procedures.

---

[4] Miller, SE, Marcatili, FAJ, and Li, T, Research Toward Optical-Fiber Transmission Systems, Part 1, Proceedings of the IEEE, vol 61, no 12, December 1973

[5] Wittke, JP, Optical Fiber Communications Link Design, Proc SPIE, vol 63, Guided Optical Communications, p 58

[6] Naval Electronics Laboratory Center Report 1763, Transfer of Information on Naval Vessels Via Fiber Optics Transmission Lines, by HF Taylor, 3 May 1971

[7] Naval Electronics Laboratory Center Report 1921, Fiber Optic Data Bus, by EA Howard and DH Marcus, 29 April 1974

[8] Naval Electronics Laboratory Center Report 1930, Fiber Optic Data Bus System, by HF Taylor, WM Caton, and AL Lewis, 26 August 1974

[9] Naval Electronics Laboratory Center Report 1969, Eight-Terminal, Bidirectional, Fiber Optic Trunk Data Bus, by DE Altman, 15 November 1975

[10] Hudson, MC, and Thiel, FL, The Star Coupler: A Unique Interconnection Component for Multimode Optical Waveguide Communications, Applied Optics, vol 13, no 11, November 1974

[11] Rockwell International, Internal Letter of 12 Feb 1975, no 75. 344-050-ITDU-021, Primary Cable Interface Board R.F. Transceiver, 10037-504

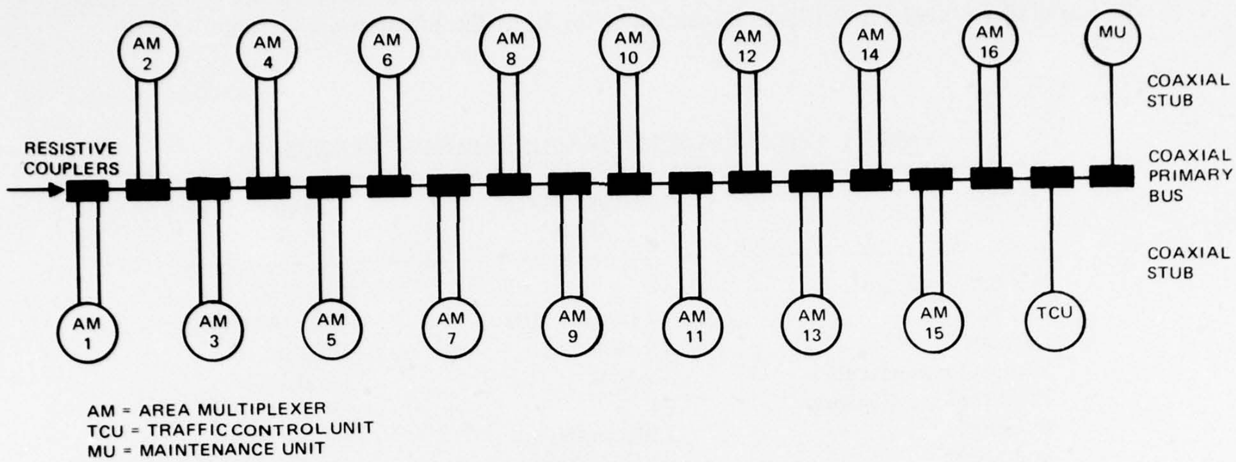

Figure 1. Maximum size SDMS primary data bus. (One of five, each serving the full complement of area multiplexers.)

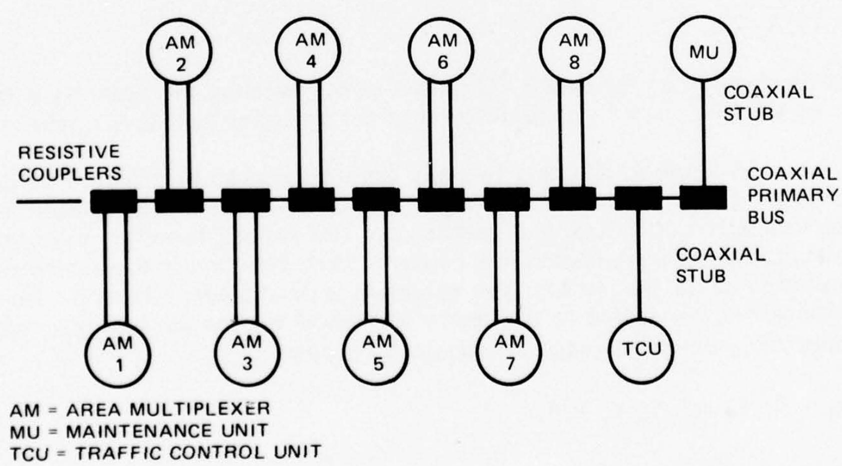

Figure 2. Nominal size SDMS primary data bus. (One of five, each serving the full complement of area multiplexers.)

Each primary bus can be as long as 1500 feet (460 m). Each area multiplexer stub can extend to 300 feet (about 90 m). The maximum path length in the system is therefore 2100 feet (640 m).

Table 1 lists the specifications that a replacement for the SDMS primary bus would be required to meet. Specifications are listed for both the maximum and nominal size SDMS.

TABLE 1. SPECIFICATIONS FOR SDMS PRIMARY DATA BUS

	Maximum Size SDMS	Nominal Size SDMS
Number of subcarriers	5	5
Pass band	40.8 – 82.8 MHz	40.8 – 82.8 MHz
Data rate	1.2 Mb/s	1.2 Mb/s
Information bandwidth	1.2 MHz	1.2 MHz
Number of access points	34	18
Bus length	1500 ft (460 m)	1500 ft (460 m)
Stub length	300 ft ($\simeq$90 m)	300 ft ($\simeq$90 m)
Bit error rate	10^{-6} errors per bit	10^{-6} errors per bit

FIBER OPTIC PRIMARY BUS CHARACTERISTICS

Figure 3 illustrates the basic fiber optic communication link. The light output of an LED transmitter is modulated by the intelligence to be transmitted and is coupled to an optical fiber transmission medium. Modulation of the light output of the LED is accomplished by modulation of its input current. At the other end of the fiber the signal intelligence is recovered by conversion of the emerging light power to a proportional electrical current, which is subsequently amplified to a usable level by a preamplifier. The signal loss in the system is given by

$$L = C_t \, A_f \, C_r, \tag{1}$$

where C_t is the fraction of the total LED output power entering the fiber, A_f is the attenuation of the fiber, and C_r is the fraction of the emerging light that reaches the photodiode.

As shown in figure 4, alternate two-way transmission can be achieved by providing both a transmitter and a receiver at each end of the fiber. Since a path division is required between the transmitter and receiver at each end of this system, however, an unavoidable factor-of-four increase in transmission loss occurs in each direction in a symmetrical system.

Adaptation of the link to bus type operation is illustrated in figure 5. Here, each fiber optic transceiver is coupled to the bus by an optical tee coupler having a coupling factor K; thus the loss between adjacent terminals becomes

$$L_{AB} = K^2 \, C_t \, A_s^2 \, A_b \, C_r \, E/4, \tag{2}$$

where we have separated the fiber optic loss into components A_s for each stub and A_b for the intervening bus fiber, and E is the coupler attenuation due to absorption, scattering, etc.

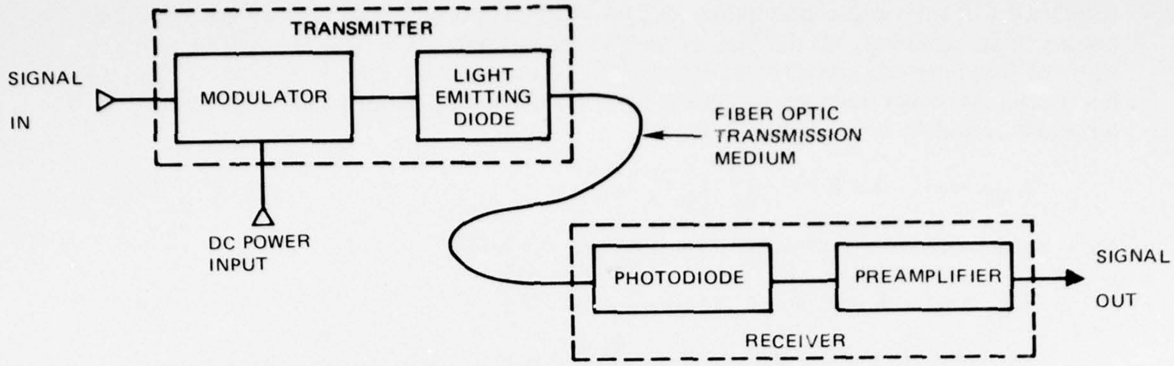

Figure 3. Basic fiber optic link.

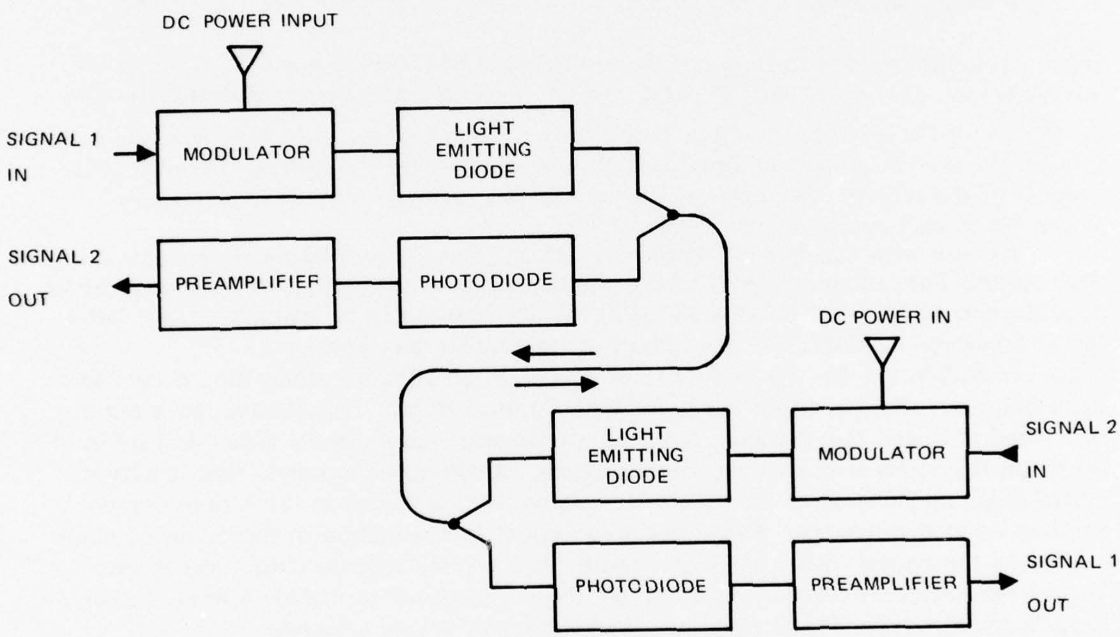

Figure 4. Bidirectional fiber optic link.

which we will call excess attenuation or loss. The insertion loss of each of the coupling points, or tee couplers, on the bus, as seen by signals already on the bus is E (1 – K); thus the loss between nonadjacent transceivers is increased by E (1 – K) for each coupling point that the signal must pass in going between the terminals involved. The loss between terminals A and C, for example, is then

$$L_{AC} = (1 - K)\, K^2\, C_t\, A_s^2\, A_b\, C_r\, E^2/4. \tag{3}$$

Between the ends of a system of n transceivers, the loss is

$$L_{1n} = (1 - K)^{n-2}\, K^2\, C_t\, A_s^2\, A_b\, C_r\, E^{n-1}/4. \tag{4}$$

An alternate buslike arrangement, known as the star or radial coupler bus, is shown in figure 6. Here, instead of being coupled in serial fashion to points along a common bus fiber, the transceiver leads are all coupled at a common point, where power radiating from each individual fiber is distributed uniformly among all of those at the junction. The power division ratio seen by a signal passing through the junction must therefore be 1/n, where n is the total number of fibers reaching the junction. The loss factor between any two stations in such a system is

$$L = C_t C_r A_F E_s/4n, \tag{5}$$

where A_F is the loss due to fiber attenuation between the terminals, and E_s is the excess loss, as before, of the star coupler. Here the loss increases more slowly with n than it did in the case of the tee coupler, where n appeared as an exponent. Also note in figure 6, though, the greater amount of signal lead required to connect the system. Detailed comparisons of the relative advantages of the tee and star systems are given in references 7, 8, and 10, as well as later in this report.

As with wire transmission, both time and frequency multiplexing are possible using fiber optics. For example, if each LED is modulated by a different radio frequency carrier or subcarrier, which is in turn modulated by the information to be transmitted, the latter can be recovered by filtering at the output of the receiver preamplifier.

In addition to the circuit losses just described, an effective attenuation occurs when radio frequency subcarriers are transmitted over optical fibers. This attenuation is due to the spread in transit time between the many propagation modes in the fiber. In base-band operation this effect is known as pulse dispersion. A difference in arrival time results in partial phase cancellation of the modulation on the optical carrier as the various components arrive at the detector. The effect is equivalent to a reduction in the degree of modulation on the optical carrier and hence results in a lowered receiver output signal level. The overall loss equations, (4) and (5), must thus be modified to include a term, A_d, to account for this dispersion attenuation. The two equations then become

$$L_{1n} = (1 - K)^{n-2}\, K^2\, C_t\, A_s^2\, A_b\, A_d\, C_r\, E^n/4 \tag{6}$$

for the tee coupler system, and

$$L_s = C_t\, C_r\, A_F\, A_d\, E_s/4n \tag{7}$$

for the star coupler system.

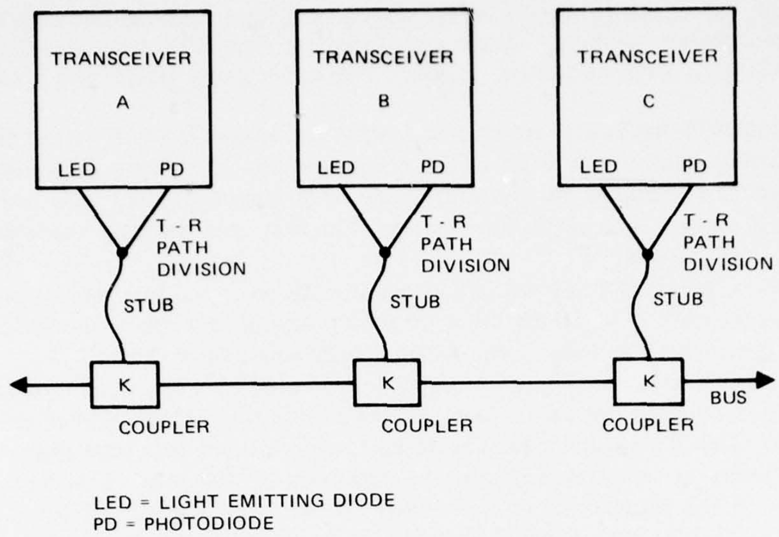

Figure 5. Fiber optic tee coupler data bus.

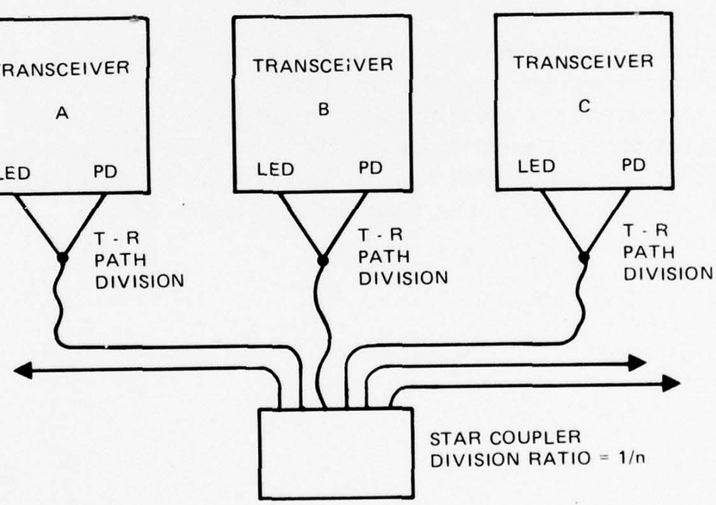

Figure 6. Fiber optic star coupler data bus.

Perhaps the most critical choice in the design of a fiber optic communications link is that of the transmission medium. At present, there are essentially three basic types from which to choose: step index fiber bundles, step index single fibers, and graded index single fibers.

Fiber bundles, being larger, are able to couple the largest fraction of the available power from a diffuse source such as an LED. Because of the cost of the quantity of materials required, fiber bundles are generally made from higher loss materials and thus have a greater attenuation than single-fiber cables. The best commercially available bundle has a loss rate of 100 dB/km.

Single fibers, on the other hand, are available with an initial loss rate as low as 6 dB/km, which increases to 16-20 dB/km after incorporation in a cable. Because of this lower loss rate, the analysis to follow will consider only single-fiber cables.

As mentioned earlier, the spread in signal transit time between the various modes of light propagation through optical fibers results in an effective attenuation of sinusoidal subcarrier signals. The graded index fiber is designed to minimize this time spread by increasing the velocity of rays traveling near the periphery of the fiber. The degree of success attainable in this direction is demonstrated by two otherwise similar fibers, Corning Type 1028 step index fiber and Type 1156 graded index fiber.[12] The frequency at which a 1 km length of this fiber will attenuate the subcarrier by 3 dB is increased from 20 MHz to 200 MHz in changing from the step index to the graded index profile. Research fibers with dispersions 1/50 of the equivalent step fibers have been made.[13] Therefore, in view of the advantage which the graded index structure provides to subcarrier systems, the analysis which follows will be based almost exclusively on this type.

BUS POWER BUDGET

The success or failure of information transfer in any communication system is determined by the minimum detectable signal level, the attenuation interposed between transmitter and receiver, and the transmitter output level. In this section we will estimate the minimum detectable signal level for the SDMS specified error rate as well as the maximum available LED power coupled into the fiber optic cable. From these, we will then determine the maximum attenuation acceptable on the bus.

---

[12] Corning Glass Works, Corning NY, Product Bulletin Number 2

[13] Lucy, GJ, Fiberguide Projections – Performance and Price, Second European Conference on Optical Fibre Communications, Organized by Groupment Des Industries Electroniques (GIEL) Societe Des Electriciens, Des Electroniciens Et Des Radioelectriciens (SEE), Paris, September 27-30 1976

MINIMUM ACCEPTABLE SIGNAL LEVEL

We will first determine the minimum signal power required at the receiver photodiode to provide the error rate required by SDMS. In reference 14, the probability of error for binary decision in Gaussian noise is shown to be

$$P_e = \frac{1 - \operatorname{erf}\dfrac{s}{2n\sqrt{2}}}{2}, \tag{8}$$

where s/n is the peak signal-to-rms-noise ratio. The plot of this expression, which is also given in reference 14, shows that for a rectangular signal form, the SDMS bit error rate of 10^{-6} errors per bit requires a peak signal-to-rms-noise ratio, at the receiver output, of 17.6 dB, corresponding to a signal-to-noise-power ratio of 57.5. The improvement in this ratio due to an FM system operating above threshold is given in reference 15 as

$$I = 3\beta^2, \tag{9}$$

where β is the modulation index, or ratio of the peak carrier frequency deviation to the modulation frequency. In the SDMS FM transmitter, the peak deviation is 1.2 MHz and the signal bandwidth is also 1.2 MHz. Thus β is equal to one, and the improvement ratio is three. For this reason, a signal-to-noise-power ratio (based on noise within the SDMS receiver pass band) of 19.2 (12.8 dB) is required at the fiber optic transceiver output to satisfy the error rate requirement of SDMS. If the transceiver preamplifier has a noise figure of 5 dB, this output signal-to-noise ratio corresponds to an input signal-to-noise power ratio of 60.6.

In the receiver the following noise sources must be considered:

Thermal noise in the photodiode load resistance

$$\left(i_{nt}\right)^2 = 4\,K\,T\,B\,/\,R_L; \tag{10}$$

signal quantum noise

$$\left(i_{ns}\right)^2 = 2\,e\,I_s\,B; \tag{11}$$

background quantum noise

$$\left(i_{nb}\right)^2 = 2\,e\,I_b\,B; \tag{12}$$

dark current quantum noise

$$\left(i_{nd}\right)^2 = 2\,e\,I_d\,B; \tag{13}$$

[14] Schwartz, M, Information Transmission Modulation and Noise, McGraw-Hill, NY 1970

[15] ITT, Reference Data for Radio Engineers, 6th Edition, Howard W Sams and Company, NY 1975

where

K is Boltzmann's constant (1.38×10^{-23} joules/kelvin),

T is the effective temperature of the resistance involved (300 kelvins),

B is the system information bandwidth (1.2 MHz),

R_L is the effective load resistance seen by the photodiode,

e is the charge on the electron (1.60×10^{-19} coulombs),

I_s is the average signal induced photocurrent,

I_b is the average background induced photocurrent ($4\ I_s$), and

I_d is the average dark current of the photodiode (10^{-8} amperes).

The background light causing I_b is the result of the other four frequency multiplexed signals which must be accommodated on the fiber. All five optical carriers contribute to the photocurrent and hence to the resultant shot noise. This effect would be the greatest when stations at the extreme ends of, for example, a 17-coupler tee system are communicating and the four transmitters adjacent to the receiver of this pair are also transmitting to their intended receivers. The noise current due to the interfering carriers would greatly exceed that due to the wanted signal. This effect can be minimized* by using attenuators in all transmitter and receiver leads except those at the ends of the system, to equalize the loss over all paths through the system to that between the end multiplexers (see appendix C). The result of this arrangement is that the interfering signals always equal the wanted signal; thus the total background induced current will be just four times as large as the wanted signal current.

The total noise with which the signal must compete is the sum of the contributions from all of the above sources; therefore the total noise

$$(i_n)^2 = (i_{nt})^2 + (i_{ns})^2 + (i_{nb})^2 + (i_{nd})^2 . \tag{14}$$

The power dissipated in the load resistance, R_L, by the signal current, i_s, must exceed that due to the noise current by the signal-to-noise-power ratio, S/N, so that

$$i_s = \left((S/N)\ (i_n)^2 \right)^{1/2}. \tag{15}$$

If k is the response of the photodiode, the required optical signal power is given by

$$P_s = \frac{i_s}{k}$$

$$= \frac{1}{k} \left((S/N)\ (i_n)^2 \right)^{1/2}, \tag{16}$$

which can also be written as

$$P_s = \frac{1}{k} \left((S/N)\ \left[(i_{nt})^2 + (i_{nd})^2 + (i_{ns})^2 + (i_{nb})^2 \right] \right)^{1/2}. \tag{17}$$

---

*The writer is indebted to HF Taylor of NELC for pointing out this fact

Recalling that the dc photocurrent, I_s, is also given by the product of photodiode response, k, and the average incident power, P_s, and the last two noise terms are functions of P_s, since $I_s = I_b/4$, we may solve for P_s to obtain the following:

$$P_S = \frac{5\ e\ b}{k}\left(\frac{S}{N}\right) + \left\{\frac{25\ e^2\ B^2}{k^2}\left(\frac{S}{N}\right) + \frac{1}{k^2}\left(\frac{S}{N}\right)[(i_{nt})^2 + (i_{nd})^2]\right\}^{1/2}. \qquad (18)$$

The response, k, of the photodiode is given by:

$$k = \frac{q\ \lambda\ e}{h\ c}, \qquad (19)$$

where q is the photodiode quantum efficiency (80 percent),

λ is the operating wavelength (820 nm),

h is Planck's constant (6.62×10^{-34} joule seconds), and

c is the velocity of light (3.00×10^8 m/s).

From the above we find that k = 0.528 amperes per watt.

To determine the thermal noise, we must first determine the photodiode load resistance, R_L. The photodiode response must cover all five 8.4 MHz subcarrier channels, or a 42 MHz bandwidth. If we use, for simplicity, a simple LC circuit as the coupling network, and we allow the response to be down 3 dB at the band edges, the required load resistance is

$$R_L = \frac{1}{2\ \pi\ BC}, \qquad (20)$$

where C is the sum of the photodiode junction, circuit, and preamplifier input capacitances. Since C will be about 10 pf, the required load resistance is about 380 ohms. With this and the values of the other terms already given, equation 10 gives the thermal noise as

$$(i_{nt})^2 = 5.23 \times 10^{-17}\ (\text{amperes})^2$$

From the typical dark current of 10^{-8} amperes, equation 13 gives the dark noise as

$$(i_{nd})^2 = 3.84 \times 10^{-21}\ (\text{amperes})^2$$

Upon evaluating the expression (18) for the required signal power, P_s, according to the assumed system parameters, we find that the required signal power is 1.07×10^{-7} watts, or -39.7 dBm. With this value for P_s and the 0.528 A/W as the response, k, of the photodiode (see eq 19), the quantum noise due to the signal and the background light are found from equations 11 and 12 to be

$$(i_{ns})^2 = 2.17 \times 10^{-20}\ (\text{amperes})^2$$

and

$(i_{nb})^2 = 8.68 \times 10^{-20}$ (amperes)^2, respectively. Comparison of these and the other components found previously shows that the thermal and preamplifier noise components are dominant.

Because the required signal level is set mainly by thermal noise, some advantage can be gained by the use of an avalanche photodiode, APD, instead of the simple PIN diode assumed in the foregoing. The APD depends upon impact ionization to provide internal photocurrent multiplication ahead of the source of thermal noise. The APD is characterized by an internal current gain factor, termed avalanche gain, G, of typically 10–100 and by an excess noise factor, f_n, which is due to the statistical nature of the ionization process. Since f_n is a function of the avalanche gain, G, it may be, for our purposes, grossly approximated[5,16] by

$$f_n \approx G^{1/2}. \tag{21}$$

The APD dark current is usually given as the sum of a surface leakage, I_{ds}, and a bulk leakage, I_{db}. Only the bulk leakage current is multiplied by the gain and excess noise factors. Thus the dark noise term of equation 17 becomes

$$(i_{nd})^2 = 2\ e\ B\ (I_{ds} + G^{2.5}\ I_{db}). \tag{22}$$

Similarly, the signal and background quantum noise terms become

$$(i_{ns})^2 = 2\ e\ B\ I_s\ G^{2.5} \tag{23}$$

and

$$(i_{nb})^2 = 2\ e\ B\ I_b\ G^{2.5}, \text{ respectively.} \tag{24}$$

When we make these substitutions in equation 17 and solve for P_s as before, we obtain

$$P_s = \frac{5\ e\ B\ G^{1/2}}{k}\left(\frac{S}{N}\right) + \left\{\left[\frac{5\ e\ B\ G^{1/2}}{k}\left(\frac{S}{N}\right)\right]^2 + \frac{S/N}{G^2\ k^2}\left[i_{nt}^{\ 2} + 2\ e\ B\left(I_{ds} + I_{db}\ G^{2.5}\right)\right]\right\}^{1/2}. \tag{25}$$

The RCA developmental APD Type C30817 is capable of a gain[17] of 50 and has bulk and surface leakage currents of 10^{-10} and 10^{-7} amperes respectively. Using these values in equation 22, we find the APD dark noise to be 7.18×10^{-19} amperes^2. This is two orders of magnitude greater than that of the PIN detector, but is still small compared to the thermal noise. Substitution of these and the previously used values in equation 25 gives the minimum usable power as

$$P_s = 3.06 \times 10^{-9}\ \text{W, or } -55.1\ \text{dBm}.$$

For comparison, we can now use this signal level to compute the total quantum noise

$$(i_{nq})^2 = (i_{ns})^2 + (i_{nb})^2$$

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[16] Webb, PP, McIntyre, RJ, and Conradi, J, Properties of Avalanche Photodiodes, RCA Review, vol 35, June 1974
[17] RCA Electronic Components, Harrison NJ, Product Sheet C30817 issued October 1972

from

$$(i_{nq})^2 = 10\, e\, B\, k\, P_s\, G^{2.5}.$$

We then find that the quantum noise, $(i_{nq})^2 = 5.49 \times 10^{-17}\ A^2$, is now of the same order of magnitude as the other noise components, and no significant improvement can be expected by increasing the APD gain beyond the value we have chosen.

RECEIVER COUPLING LOSS

As mentioned previously, if the receiver photodiode surface is too small to intercept all of the light emerging from the fiber, an additional loss factor C_r must be included to account for the lost light. However, the use of a combination such as the Corning Type 1302 graded index fiber with the RCA Type C30817 APD results in a photosurface diameter 13 times that of the fiber core. Hence, either bringing the fiber core close enough to the photosurface or using a suitable lens to image the fiber core onto the photosurface should make this loss negligible.

MAXIMUM AVAILABLE TRANSMITTER POWER

Available LED output powers range upward to as much as several milliwatts. Recent developments in edge emitting LEDs have permitted coupling as much as 0.8 mW (–1 dBm) into a single multimode step index fiber having a 0.14 numerical aperture and a 90 μm core diameter.[18] Several milliwatts can be coupled into a similar fiber from an injection laser, such as the RCA developmental type C30127, through the use of suitable optics.[5]

MAXIMUM PERMISSIBLE BUS LOSS

If the –1 dBm LED described above is used as a transmitter, the –55 dBm APD receiver power requirement allows a total bus loss of 54 dB. If we choose to use an injection laser, we should be able to couple in to the fiber at least 5 mW (+7 dBm), which would allow a bus loss of 62 dB.

FIBER OPTIC TRANSCEIVER

The fiber optic transceiver serves the function of an interface between the optical fiber and the output terminal of the area multiplexer. It serves to take the frequency modulated rf carrier from the area multiplexer and use it as a subcarrier to modulate the LED or laser optical source. It also serves to demodulate optical carriers coming from the bus, then to amplify the resultant rf carrier and present it to the area multiplexer input terminal.

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[18] Wittke, JP, Ettenberg, M, and Kressel, H, High Radiance LED for Single-Fiber Optical Links, RCA Rev, vol 37, no 2, June 1976

The transceiver and its connection to the area multiplexer are shown in block form in figure 7. In this figure, the rf signal from the area multiplexer is amplified as necessary by the LED driver and then, in combination with the dc bias necessary for linear LED operation, is used to operate the LED. The output of the LED, as described in one of the options of appendix C, passes through a pair of optical attenuators, A, to the junctions with the left- and right-directed stubs. Any of the other options described there could be used instead. From these junctions, signals originating from sources to the left and right are separately adjusted in level and directed to the photodiode. The rf signal out of the photodiode is amplified by the preamplifier to a level suitable for presentation to the area multiplexer.

It is apparent from the figure that a stability problem is inherent in the common input and output terminal of the area multiplexer, as far as the operation of the transceiver is concerned. Noise from the preamplifier can be amplified by the LED driver, can modulate the LED, and then, by backscatter from the transmitter-receiver path division point, D, can be returned to the receiver input for further amplification.

Electronically, the simplest cure for the problem would be to have separate input and output terminals on the area multiplexer, but in practice this would no doubt result in a panel space problem and would preclude a one-for-one comparison of the wire and fiber optic busses. Furthermore, it would violate the initial stipulation that no change in SDMS would be required for application of fiber optics.

Figure 8 illustrates a way of avoiding the receiver-to-transmitter feedback problem and at the same time providing for gating off the optical carrier when the area multiplexer is not transmitting. In this figure, the signal being fed into the area multiplexer is separated from that coming out by means of the hybrid transformer, T. Because of the symmetrical location of the tap on the transformer primary winding and the equality of R_2 with the combination of R_1 and the area multiplexer and LED driver input impedances at the ends of the primary winding, the signal from the preamplifier couples to the area multiplexer input but not to the transformer secondary winding. The signal coming from the area multiplexer, however, couples through the transformer to the detector that is connected to its secondary. Thus, an output from the detector occurs, essentially, only when the area multiplexer is transmitting. In addition, to ease the balance requirement on the hybrid transformer, a thresholding device allows the output of the detector to couple through only after reaching some predetermined level. By this means, leakage signals due to lack of perfect balance between the hybrid transformer windings are ignored as long as they can be kept small relative to the coupled signals. The signal from the thresholding device is used to operate a gate controlling both the bias and rf modulation on the LED. To prevent instability during the time that the LED is transmitting, the receiver output lead is broken by an opposite polarity gate. The load resistors R_1 and the R_2 combination are made sufficiently high to constitute a negligible load on the area multiplexer output; their ratio is set by adjusting R_2 so as to equalize the currents from the preamplifier flowing in the two halves of the transformer primary. The loss seen by the signal from the preamplifier is of little concern since the signal-to-noise ratio has already been established at that point.

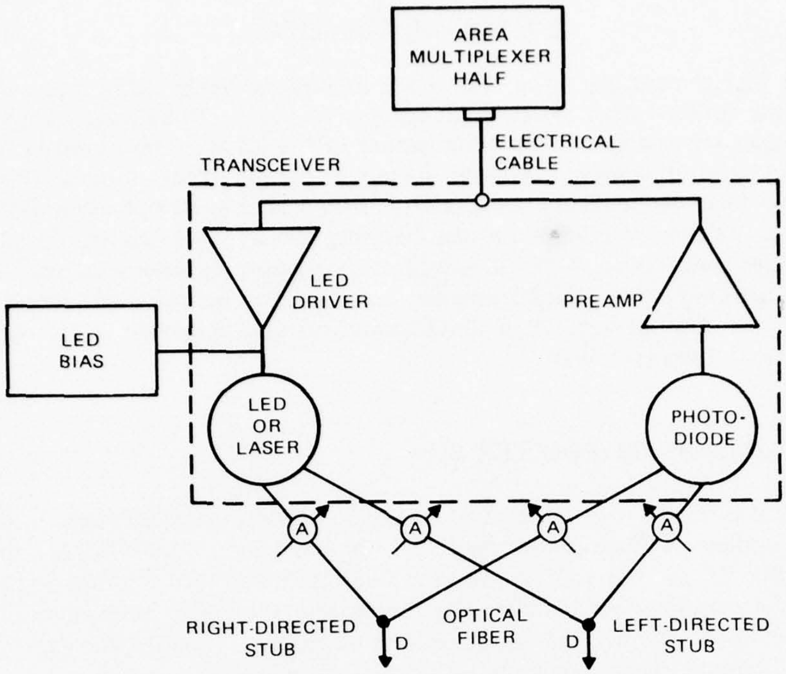

Figure 7. Transceiver functional diagram.

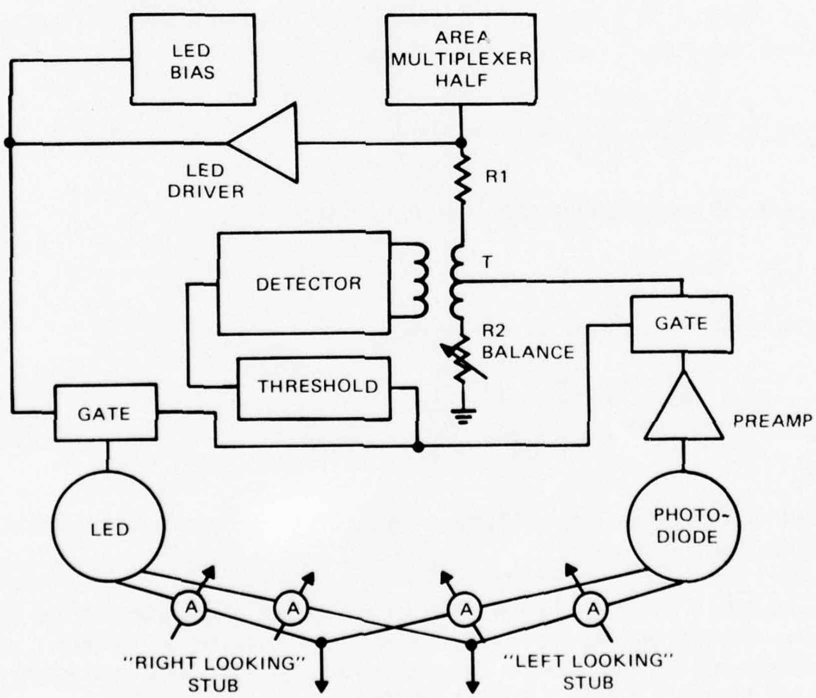

Figure 8. Transceiver with LED gating to prevent instability.

TEE COUPLER SYSTEM

A fiber replacement bus using optical tee couplers is illustrated in figure 9. It is apparent that the configuration closely matches that of the electrical bus of figure 1. The optical tee coupler serves a system function similar to the isolation taps used in the coaxial system, but its operation is more closely analogous to the microwave directional coupler. For example, no lossy elements are deliberately introduced, and its operation is characterized by a fixed signal division ratio known as the coupling factor. To minimize the number of coupler-to-coupler connections required as well as to conform as closely as possible to the SDMS configuration, each coupler provides two taps to serve the dual redundant stubs leading to each area multiplexer. A separate transceiver unit is located at the output terminal of each area multiplexer half.

END-TO-END LOSS OF TEE COUPLER BUS

The worst case end-to-end transmission loss in a system such as figure 9, consisting of n dual tap couplers, is illustrated in figure 10. In this figure, A_s and A_b are the attenuation factors due to one stub and to the total fiber attenuation of the bus, respectively; while k is the tap coupling factor, defined as the ratio of the power coupled to one stub to that incident on the coupler and is, for reasons of practical logistics, the same for all couplers.* Each coupler is also characterized by (1) a transmission loss, $T = 1 - 2k$, which accounts for the power extracted by the taps, and (2) an excess loss, E, which includes all remaining losses (connectors, Fresnel reflections, scattering, absorption, etc). For simplicity, E is assumed to be the same for all couplers. An additional loss factor of two occurs at each transceiver due to division of the optical path between transmitter and receiver. The end-to-end transmission loss is then evidently

$$L_{1n} = \left(\frac{A_s^2 A_b E^n}{4}\right) \left[k^2 (1 - 2k)^{n-2}\right] . \tag{26}$$

Letting $dL_{1n}/dk = 0$ gives the minimum loss value of k as

$$k = 1. \qquad (n > 2) \tag{27}$$

With this value of k, the end-to-end loss becomes

$$L_{1n} = \left(\frac{A_s^2 A_b E^n}{4}\right) \left[\frac{\left(1 - \frac{2}{n}\right)^{n-2}}{n^2}\right]. \tag{28}$$

The first group of terms represents dissipative losses; the second represents coupled power losses due to the taps.

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*A saving of several dB can be gained by a separate choice of k for each coupler stub such that only the power required is coupled to each tap. This technique is discussed rather extensively in references 8 and 9. Its utilization, however, requires either that k be made adjustable or that a very large stock of different k couplers be kept on hand. A practical method of making k adjustable has not as yet been developed; and to stock a large number of couplers would, at present, appear to create a considerable logistics problem. Therefore, this technique is not considered in this study.

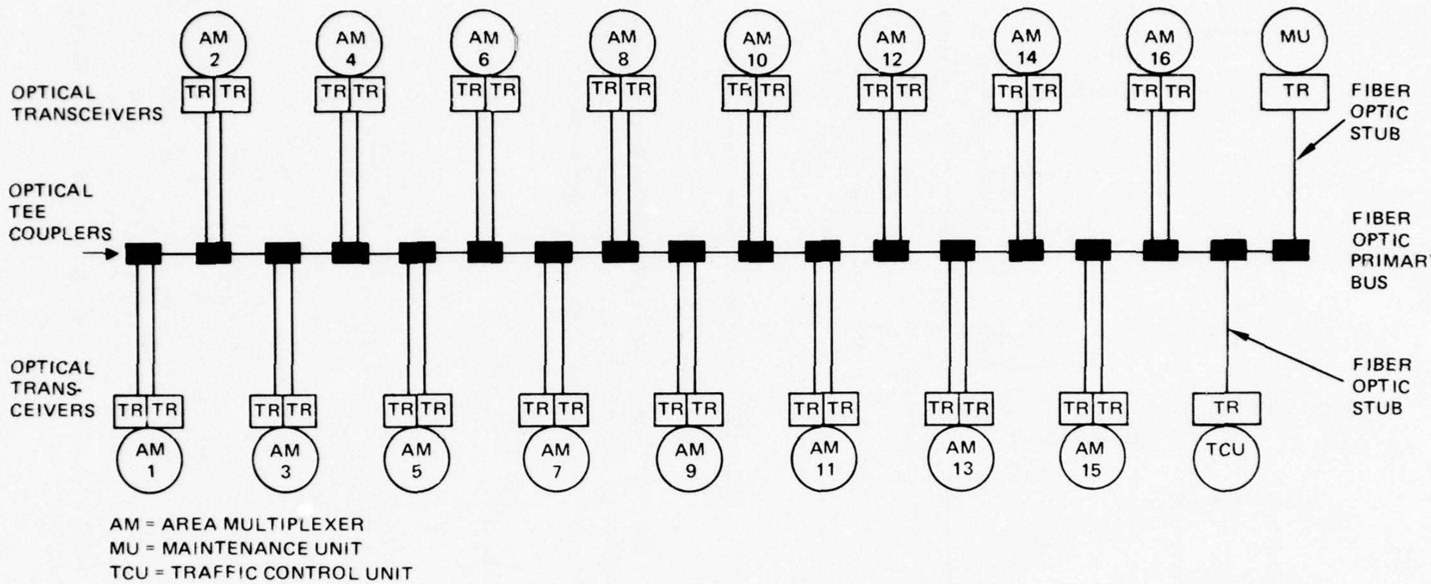

Figure 9. Fiber optic primary data bus using tee couplers.

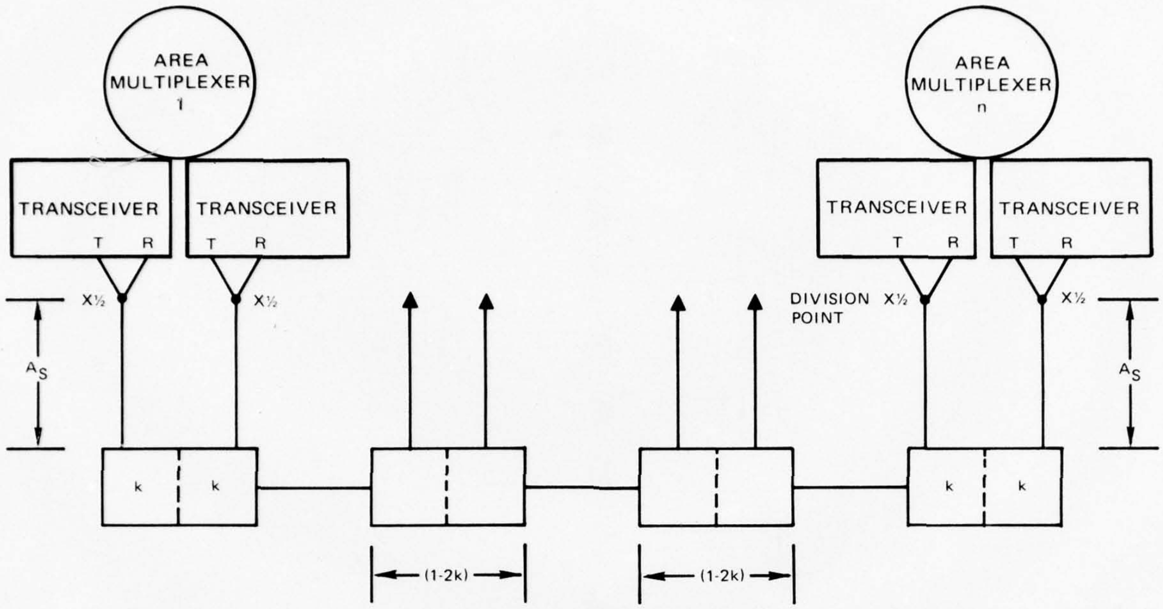

Figure 10. End-to-end loss on tee coupler bus.

In addition to the above losses, we must add the term A_d to account for demodulation of the optical carrier by pulse dispersion in the fiber optic cable. The complete expression for the end-to-end transmission loss of the bus is then

$$L_{1n} = \left(\frac{A_s^2 A_b}{4}\right) E^n \left[\frac{(1-\frac{2}{n})^{n-2}}{n^2}\right] A_d . \tag{29}$$

That portion of the loss given by equation 29 which is dependent on the number of couplers, n, served by the bus is

$$E^n\left[n^{-2}\left(1-\frac{2}{n}\right)^{n-2}\right].$$

This term is plotted in figure 11 as a function of n, with the coupler excess loss, E, as a parameter. As stated previously, the coupler excess loss comprises all losses beyond that due to the power taken out by the stubs. In the case where connectors are provided on the coupler, their loss can also be most conveniently included in the excess loss. Thus, the total end-to-end loss of an n-station bus can be found by first finding the n-dependent loss from figure 11 and then adding the number of dB representing the fiber optic dependent loss terms,

$$A_s^2\ A_b\ A_d/4.$$

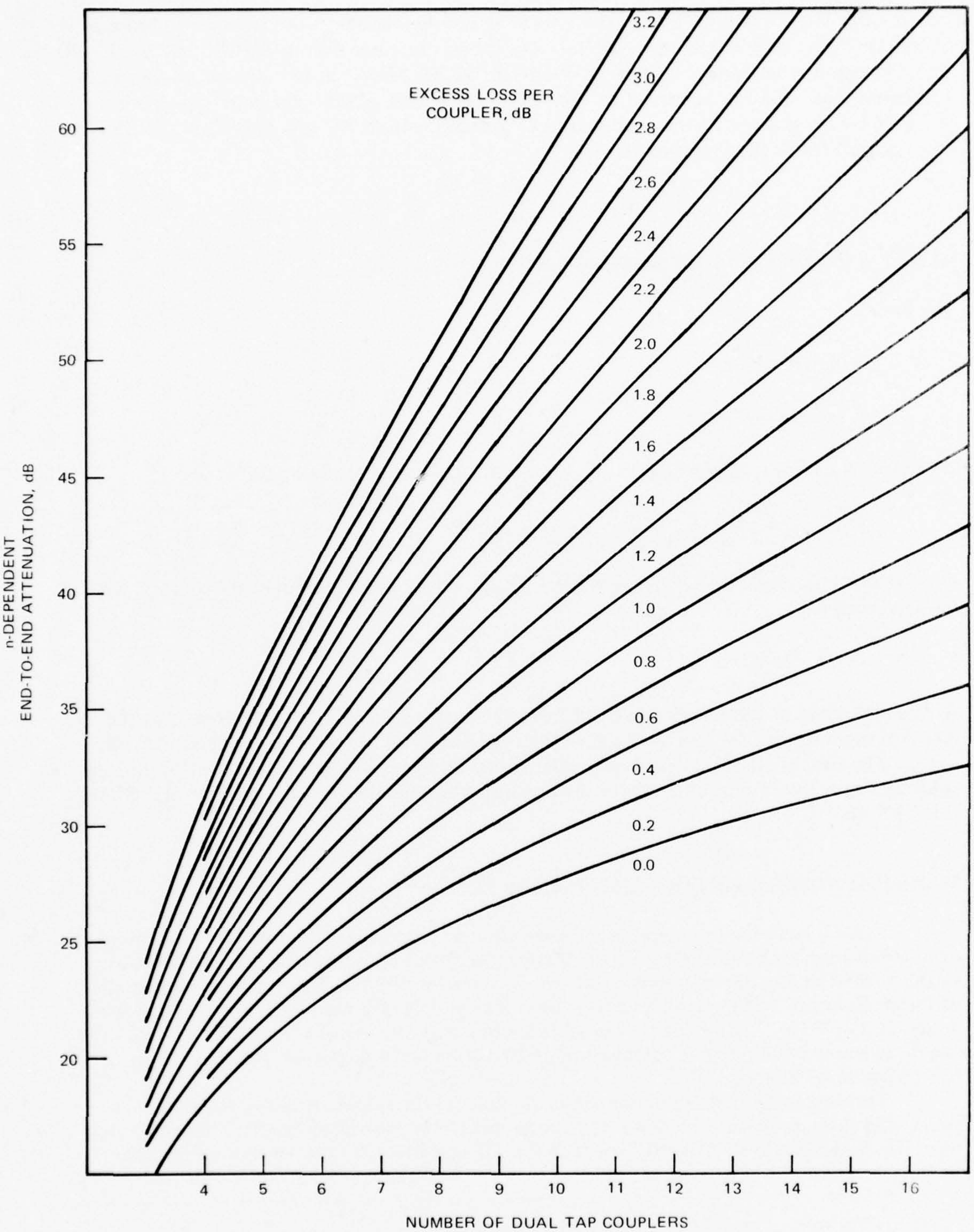

Figure 11. Bus loss. n-dependent end-to-end loss of tee coupler bus as a function of the number of dual tap couplers used and total excess loss.

For the Corning Coreguide Type 1302 graded index fiber cable,[19] the loss rate is given as 20 dB/km. The sum of the stub and bus loss for the full size 640 m SDMS is then 12.8 dB. The dispersion induced loss is given as 3 dB/km, at 200 MHz. In the absence of any better scaling method, this can be scaled to the upper end of the SDMS subcarrier pass band (82.8 MHz) by analogy to the attenuation of a single section RC low pass filter of time constant τ. The scaling relation is

$$L = (1 + 3r^2)^{-\frac{1}{2}*},$$

where r is the ratio of the frequency at which the loss is 3 dB.

The loss is

$$L = X_c/(R + X_c)$$
$$= (\tau^2 \omega^2 - 1)^{-\frac{1}{2}}.$$

If the loss is L_1 at ω_1 and the loss is L_2 at ω_2, it follows that the loss ratio

$$L_1/L_2 = (L_1^2 + (\omega_2/\omega_1)^2 - L_1 (\omega_2/\omega_1)^2)^{\frac{1}{2}}.$$

If we then let L_1 equal 0.5 when ω_1 is the 3 dB frequency and substitute r for ω_2/ω_1, the desired result is

$$L_2 = (1 - 3r^2)^{-\frac{1}{2}}.$$

At the upper end of the SDMS pass band this relation gives the loss as 0.9 dB/km. For the 0.64 km cable length, the loss due to the effects of dispersion should thus be about 0.5 dB.

The sum of all of the fiber optic related loss terms, as well as the factor-of-four beam splitting loss is thus about 19.3 dB for the maximum size SDMS. For the nominal size SDMS it is 14.9 dB.

MAXIMUM NUMBER OF COUPLERS ON TEE BUS

Table 2 has been prepared on the same basis to provide quick reference to the number of dual tap couplers with APD detectors that can be served by a single fiber optic data bus. In this table, the number of couplers that can be served is listed as a function of the length of the primary bus and the coupler excess loss. The stub length was assumed to remain fixed at 300 feet (≈90 m). The values in the table are based on the use of Corning Type 1302 cable, which, as stated earlier, has an attenuation of 20 dB/km and a dispersion induced loss of 0.9 dB/km at 82.8 MHz.

The data presented in the table indicate that (1) the specifications of the maximum size SDMS primary bus can be met if the excess loss of the individual coupler-connector combination can be reduced to slightly less than 0.6 dB; and that (2) those of the nominal size

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[19] Corning Glass Works, Corning NY, Product Bulletin Number 4

*This relation results from manipulation of the usual expression for the loss imposed on a signal of circular frequency ω by a low pass filter having series resistance R, shunt capacitive reactance X_c, and time constant τ.

TABLE 2. DUAL TAP TEE COUPLER CAPACITY.*

EXCESS LOSS, dB

Primary Bus Length, feet (metres)	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0
1500 (457)	>17	16	14	12	11	10	9	9	8	7	7	7	6	6
1400 (426)	>17	17	14	13	11	10	9	9	8	8	7	7	6	6
1300 (396)	>17	>17	15	13	12	11	10	9	8	8	7	7	7	6
1200 (365)	>17	>17	15	13	12	11	10	9	9	8	8	7	7	6
1100 (335)	>17	>17	16	14	12	11	10	9	9	8	8	7	7	6
1000 (305)	>17	>17	16	14	13	11	10	10	9	8	8	7	7	7
900 (275)	>17	>17	17	15	13	12	11	10	9	9	8	8	7	7
800 (244)	>17	>17	>17	15	13	12	11	10	9	9	8	8	7	7
700 (213)	>17	>17	>17	16	14	12	11	11	10	9	9	8	8	7
600 (183)	>17	>17	>17	16	14	13	12	11	10	9	9	8	8	7
500 (152)	>17	>17	>17	16	14	13	12	11	10	9	9	8	8	7

*Number of dual tap tee couplers that can be served as a function of coupler excess loss and length of primary bus trunk, based on figure 11, and assuming the use of an APD detector, 300 foot (91 m) stubs, and 20 dB/km cable.

SDMS primary bus can be met when the excess loss is as much as 1.8 dB. Very little experimental information exists from which to estimate the excess loss to be expected from single-fiber couplers (see appendix D). Pan[20] reports an experimental single-fiber coupler having an insertion loss of 0.6-0.8 dB at a coupling factor of 10 dB. The coupling factor required of the maximum size SDMS is only 12.3 dB, which should allow some reduction in this loss, but whether it could be reduced sufficiently to allow for the losses due to connectors on the couplers is not clear. Connectors would be required to permit coupler removal for servicing, as well as to facilitate installation. A goal of 0.2 dB per connector should be physically realizable since single-fiber splices with losses in this range have been reported by a number of investigators. Miller,[21] for example, reports an average loss of 0.073 dB for a series of splices, and Guttmann et al[22] have produced an experimental, single-fiber connector having a loss of only 0.1 dB. In view of these developments, the nominal size SDMS would appear to be feasible.

[20] Pan, JJ, Fiber Optic Directional Coupler, OSA/IEEE Conference on Laser and Electro-optical Systems, San Diego California, 25-27 May 1976

[21] Miller, CM, Loose Tube Splices for Optical Fibers, First European Conference on Optical Fiber Communications, Organized by the Electronics Division of the Institution of Electrical Engineers, 16-18 September 1975

[22] Guttmann, J, Krumpholz, O, Pfeiffer, E, Multi-Pole Optical Fiber-Fiber Connector, First European Conference on Optical Fiber Communication, Organized by the Electronics Division of the Institution of Electrical Engineers, 16-18 September 1975

LOW LOSS SINGLE-FIBER TEE COUPLER SYSTEMS

In an effort to explore the possibilities of couplers of extremely low loss for single fibers, the coupler design described in appendix A was conceived. Three of the coupler configurations considered there have theoretical lower limit excess losses lower than the 0.2 dB per coupler requirement. Whether such low losses could, in fact, be realized would have to be determined by experiment.

A bus configuration that would take advantage of the coupler design presented in appendix A is shown in figure 12. In this configuration, each transceiver has dual light sources and photodetectors, each coupling to opposite propagation directions on the dual redundant primary bus. As described in the appendix, coupling is by means of an index matched area between the fibers where the cladding has been removed. Extension of such an area along the fibers can yield a maximum coupling factor of 50 percent. Its extension along the junction between the dual redundant bus fibers provides added redundancy because the coupled area will maintain transmission following failure of alternate fibers on opposite sides of the coupler.

Extension of this concept so as to increase the effective redundancy of the stubs is illustrated in figure 13. Here, coupling is provided between the dual stubs at both the coupler and transceiver terminations so that failure of either stub results in a 3 dB increase in attenuation rather than complete failure of the stub. This configuration permits the use of either dual or single source and detector units as desired, since each unit couples to the bus in both directions. Dual sources provide source redundancy but in accordance with what is sometimes referred to as the law of conservation of brightness, they do not provide added source power. Similarly, a mirror intercepting the extra stub at M in figure 12 would permit bidirectional operation with a single source and detector in instances where the redundancy is not required. With this latter arrangement, however, the right- and left-directed coupling factors become unequal when they are large, because the signal is smaller on the second pass through the coupler.

STAR COUPLER SYSTEM

The star coupler system (fig 14) avoids much of the loss of the tee coupler system by what might be termed parallel (rather than series) connection of the taps.[10] The longest optical path for a maximum size SDMS is through one rather than 34 couplers. As shown in the figure, interconnection between area multiplexers is made at a common junction known as the star coupler. Separate fibers are run from the transmitter of each area multiplexer half to the coupler input, and from the coupler output to the receiver of each area multiplexer half. Within the star coupler, light from each transmitting fiber diverges in traversing a glass mixing block so as to be uniformly distributed over the ends of the receiving fibers at the other end of the block.

The reflective star coupler described by Hudson and Thiel[10] is shown in figure 15. In the reflective star coupler, the light path is reflected back on itself by a mirror at the far end of the mixing block. In this arrangement each cable carries both transmit and receive signals, and power division must be used to couple both transmitter and receiver to the single cable. A symmetrical power divider results in a factor-of-two loss in both the transmitter and the receiver signal and hence a 6 dB increase in system attenuation. The important advantage of this system over the nonreflective one is that it uses only half as many cables.

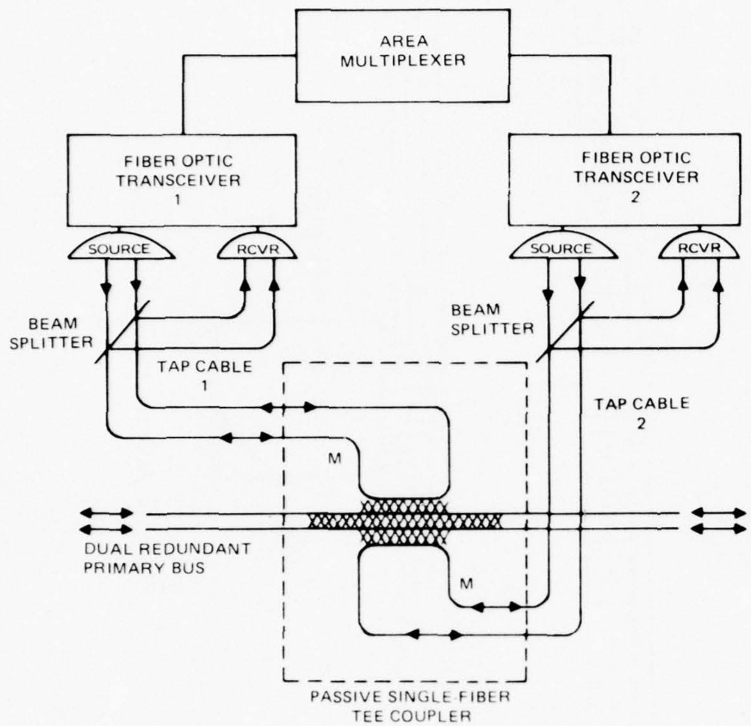

Figure 12. Low loss single-fiber coupler bus.

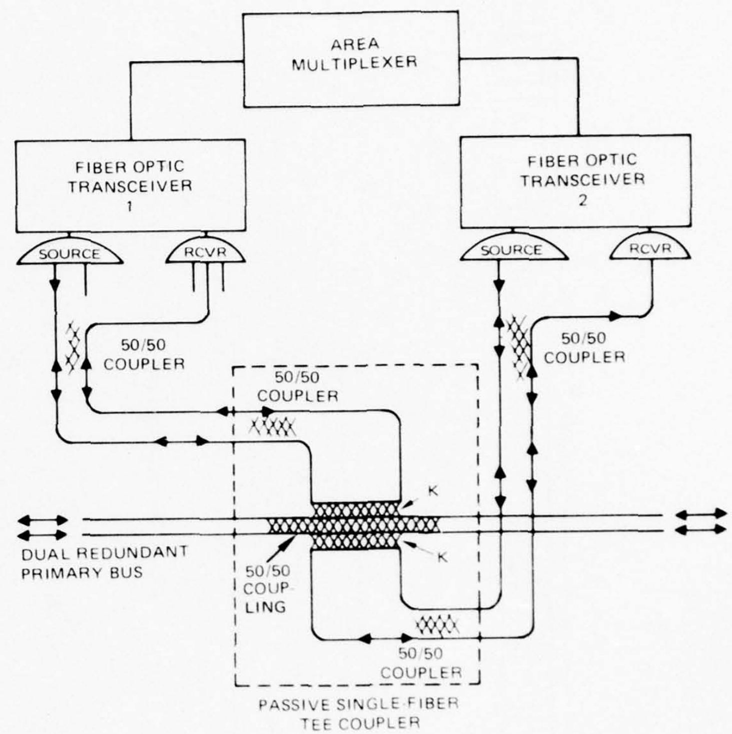

Figure 13. Low loss single-fiber coupler bus using fiber-to-fiber coupling between stubs for added conductor redundancy.

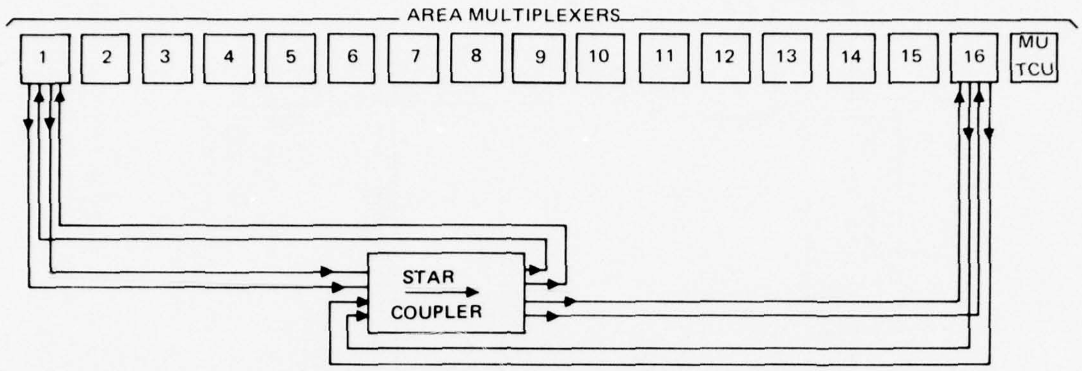

Figure 14. Transmissive star coupler bus.

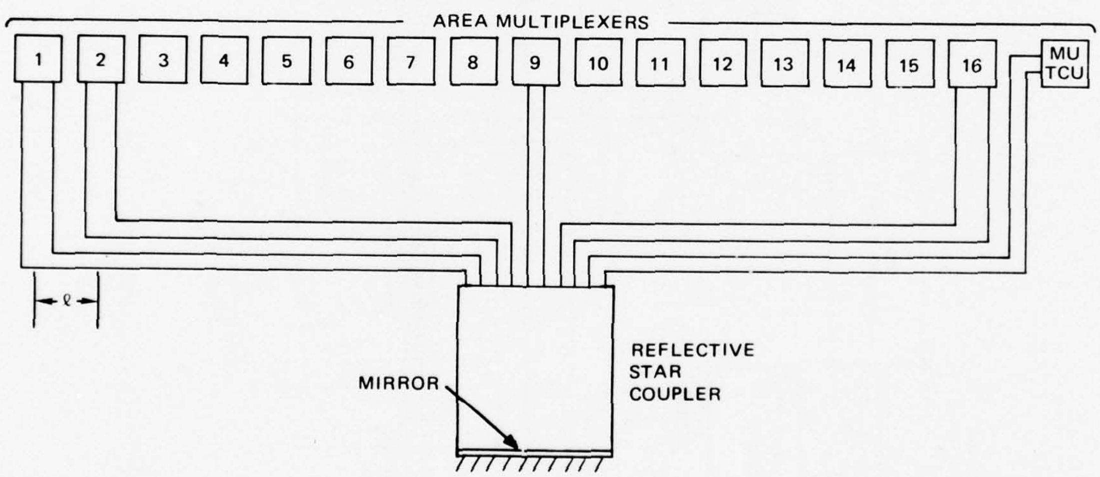

Figure 15. Reflective star coupler bus.

END-TO-END LOSS OF STAR COUPLER BUS

In a reflective star coupler system, the losses external to the coupler consist of the 6 dB transceiver beam splitting loss and the cable attenuation. In the worst case, the latter is the same as that for the tee coupler system since the cable follows the same route.

The coupler internal loss comprises three major components. First, an effective attenuation factor of n occurs, where n is the number of taps, because each input signal is divided among all the output taps. Second, a packing factor loss expresses the factor by which the area of the mixing block output face exceeds the area covered by the output fiber cores. Third, losses analogous to the excess loss of the tee coupler include absorption and scattering in the bulk of the diffusing block, surface scattering by imperfections on its surface, and reflective losses at the mirror surface. Finally, if it is not eliminated by anti-reflection coating or index matching, Fresnel reflection occurs at the input and output interfaces. Combining these losses, the end-to-end loss

$$L_{1n} = \frac{P_f A_c A_r E}{4n} , \tag{30}$$

where

P_f = packing factor loss

A_c = total cable attenuation

A_r = Fresnel reflection loss

E = "excess loss"

and the factor of 4 is the beam splitting loss at the transceiver.

The packing factor loss is dependent, to some degree, on the arrangement of the fiber-to-mixing-block interface. It is desirable to have the largest possible interface area between the mixing block surface and fiber core, with the smallest possible cladded surface on the mixing block. The configuration shown in figure 16 fulfills this requirement: the mixing block thickness equals the fiber core diameter and the fibers are aligned in a single row along its edge. The packing factor (ratio of total core area to mixing block cross-sectional area)

$$P_f = \frac{\pi N(d^2/4)}{[(N-1)D + d]\ d} , \tag{31}$$

where

N = number of fibers (same as the number of taps in the tee coupler system)

D = outside diameter of fiber

d = core diameter.

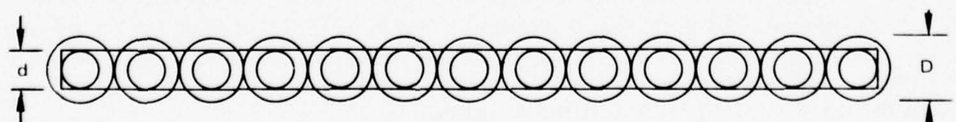

Figure 16. Star coupler mixing block.

The Corning 20 dB/km graded index fiber Type 1302, described earlier, has a core cladding ratio d/D of 1/2. With this value, equation 31 yields a packing factor loss of 40 percent (equivalent to 4 dB) for the 34-tap SDMS. The arrangement shown in figure 16 has an advantage of 3 dB over one in which the block thickness equals the outside diameter of the fiber.

The end-to-end loss of the SDMS star coupler bus is itemized as follows:

End-to-end loss	Loss, dB: Nominal size SDMS (18 taps)	Loss, dB: Maximum size SDMS (34 taps)
Power division	12.3	15.3
Cable attenuation (640 m @ 16 dB/km) (See table 1)	10.2	10.2
Packing factor	4.0	4.0
Fresnel effect (four surfaces)	0.7	0.7
Transceiver beam splitting	6.0	6.0
Estimated excess loss (includes mirror loss)	3.0	3.0
Total	36.2	39.2

Since the use of a −1 dBm LED transmitter permits a bus loss of 54 dB to be accommodated (see Maximum Permissible Bus Loss), this table shows that for the maximum size SDMS, a star coupler system provides a 14.8 dB excess over the minimum signal required at the receiver APD; and for a nominal size system it provides a 17.8 dB excess.

CABLING REQUIREMENTS OF STAR COUPLER SYSTEM

As figure 15 shows, the star coupler cable layout can be made to match that of the SDMS conventional electrical bus. Stub lengths in this configuration are the same as those in the tee coupler system. The bus portion, on the other hand, requires a separate fiber for each tap. (Each area multiplexer requires two fibers.) If the area multiplexers are spaced by a distance, ℓ, and the coupler is located in the center of the system athwart area multiplexer 9, the total fiber length required for the trunk portion of the system

$$\ell_t = 4\ell \left(1 + 2 + 3 + 4 + \ldots + \frac{N-1}{2} \right),$$

where N is odd and represents the number of area multiplexers in the system. For the maximum size SDMS, N is 17 (including an MU/TCU), and ℓ_t equals 144ℓ. For a 1500 foot (460 m) SDMS trunk, ℓ equals 93.75 feet (28.6 m); thus for the trunk portion of a star system, 13 500 feet (4115 m) of fiber is required. This is 12 000 feet (3657 m) more than the tee coupler system requires. For the nominal size SDMS, N is 9, ℓ_t is 40ℓ, ℓ is 100 feet (30.5 m); thus 4000 feet (1219 m) of fiber would be required. This is 3200 feet (975 m) more than the nominal size tee coupler bus requires.

Objections raised to this extra fiber requirement are (1) the added space and weight required, (2) the added installation cost, and (3) the added cable cost, in that order of importance. On examination, however, these objections have little significance.

The size and weight of a jacketed fiber optic cable are determined by environmental requirements rather than by the number of fibers it contains. A 17-fiber cable rugged enough for shipboard installation does not have to be significantly larger or heavier than one containing a single fiber. And such a fiber cable could be made significantly lighter than the RG-218/U coaxial cable presently used. A single 17-fiber cable could serve as the trunk of the star system, following the same route and occupying no more space than either the tee or coaxial busses. Stubs can be attached to this main trunk by a clamp-on connector assembly having a side connector to which one fiber pair is brought out. The other fibers would merely pass through the connector assembly without interruption. Thus, the connector assemblies would not induce recurring losses on the trunk. The stub connector loss is applied to any one signal path only twice and hence would not have to be as low as the loss in a tee system connector.

The only increase in installation costs would be that of placing clamp-on connectors on the trunk cable. At least until refined field installation procedures can be developed, it would seem desirable to assemble the stub connectors on the trunk prior to its installation on shipboard. The connector would have to be designed with the trunk installation procedure in mind; eg, is the cable to be placed in cable trays or pulled through cable ducts?

Although cable cost for the star coupler system is higher than for a tee coupler system, the total expenditure for cable is a small fraction of total system cost. As an example of cable cost at current prices, a cable having ten graded index fibers will soon be available from Corning Glass Works at 20 to 30 dollars per metre.* Two of these would serve the trunk requirements of an SDMS star system, and would cost at most about $28k. Most of that cost, for the optical fibers themselves, will probably decrease greatly with increasing demand and production volume. A 17-fiber cable could, of course, be made for production installation.

STAR COUPLER DESIGN

Figure 17 shows how a suitable star coupler might be fabricated from Corning 10-fiber cable. A typical set of dimensions is included. The mixing block consists of a glass slab the thickness of the fiber core diameter and just wide enough to accommodate 34 fibers. The distribution of each input signal must be uniform over the array of fibers. Uniformity is ensured by a mixing block long enough that the input signal beam spread is several times the block width. The mirror end of the block, opposite the fibers, is vapor coated with gold or silver for high reflectivity.

The moderately exacting job of attaching the thirty-four 5 mil diameter fibers to the end of the 2.5 mil thick mixing block can be simplified by the method shown in figure 18A. The mixing block (A) is cemented for support to a thicker glass slab (B) and is then ground to the specified 2.5 mils (62.5 μm) and polished. The thicker glass slab and cement have a refractive index well below that of the mixing block to preserve the numerical aperture of the system. The individual fibers extending from the cable jacket clamps, not shown, are cemented in a close-packed single row to the top of the fiber mounting block (C), as

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* Private communication with AF Fairaizl of Corning Glass Works, 11 June 1976

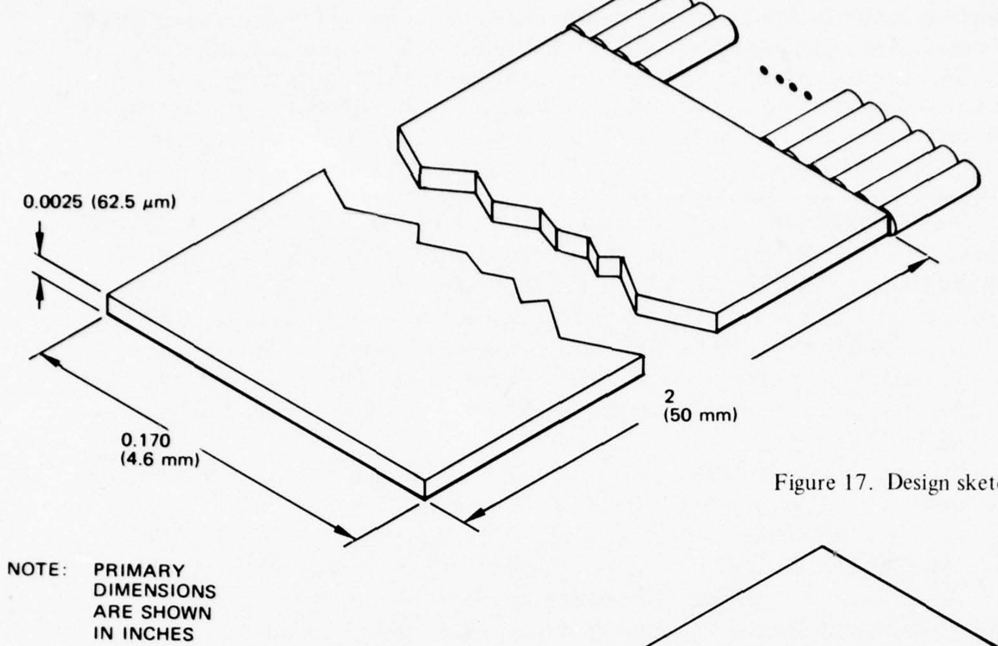

Figure 17. Design sketch of SDMS star coupler.

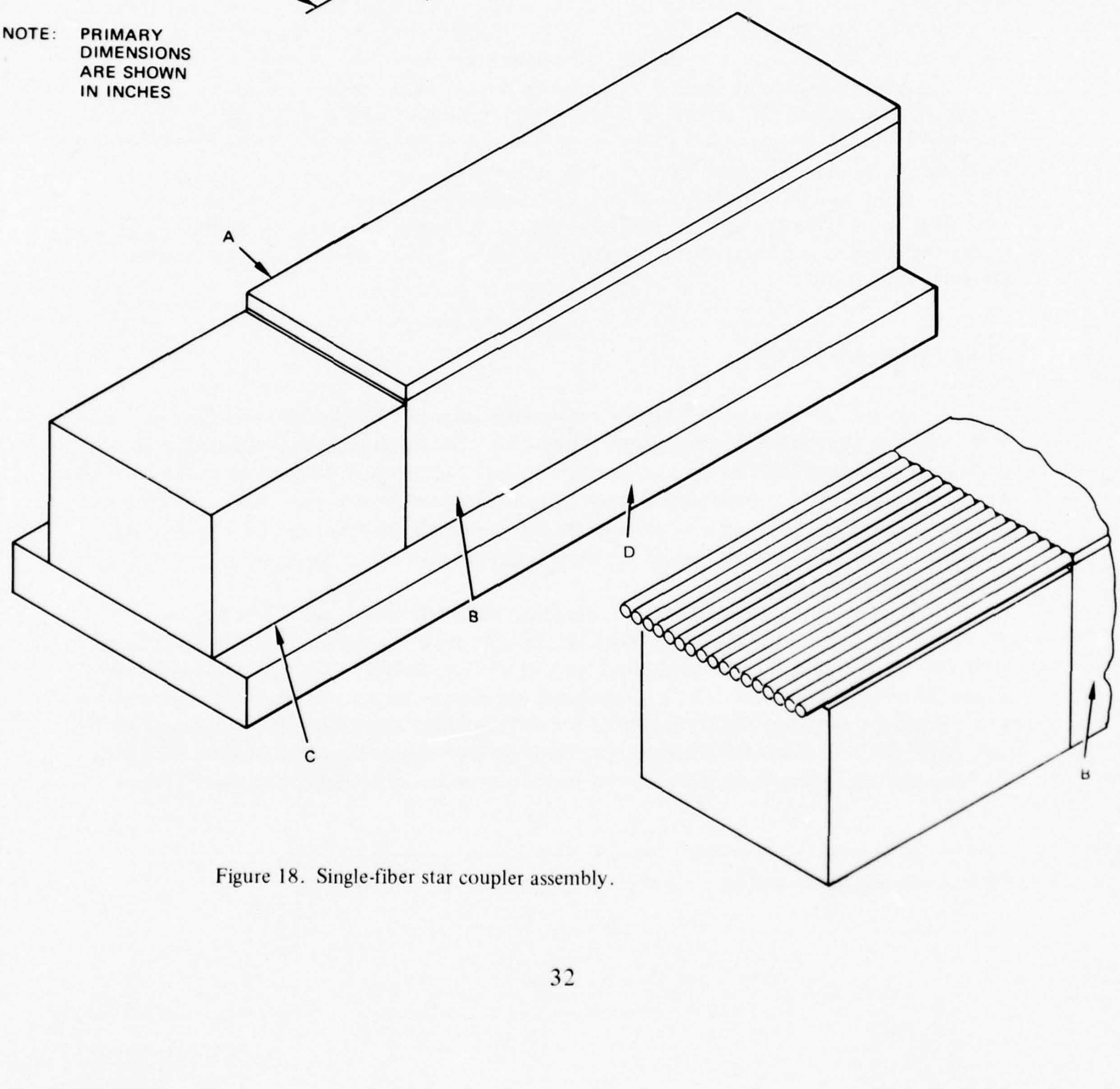

Figure 18. Single-fiber star coupler assembly.

shown in figure 18B, and the fiber ends and the end of the mounting block are then ground and polished to form matching surfaces. The thickness dimension of the fiber mounting block (C) is 1.25 mils (31 μm) less than that of the mixing block mount; this places the fiber cores in precise alignment with the edge of the mixing block when the two blocks (B and C) are mounted on the glass base (D).

The four glass pieces probably can be produced to adequate tolerances by present optical finishing techniques. Arrangement of the 34 fiber ends on the mounting block could probably be most easily done by first positioning them, one at a time, on a piece of pressure sensitive tape and then cementing the opposite side of the array to the block. After the cement has set, the tape can be removed with solvent. A pair of flats could be butted against the sides of the mounting block to provide precise transverse positioning during the cementing process. Fabrication in this manner would not appear to be very difficult, in spite of the small size of the fibers and diffusing block.

Connectors to permit separation of the coupler from the trunk cables could consist of modified multipin electrical connectors. As with the stub connectors, the loss need not be extremely low since a given signal path traverses the connector only twice. Although modification of electrical connectors for use with fiber bundles has been achieved, modification to make them suitable for the more stringent requirements of single-fiber connection would require a moderate development effort.

ACTIVE TEE COUPLERS

Incorporating signal amplification in the tee coupler provides a way of overcoming coupler loss so as to make feasible a 34-tap tee coupler bus. Having active components in the main signal path, however, decreases system reliability. Failure of the gain mechanism in one coupler of such a system would be equivalent to a break in the bus at that point.

Several ways of avoiding this problem can be devised, all involving some type of signal path redundancy. For example, automatic switching may be used in the event of amplifier failure to reroute the signal path through another amplifier or through a direct (unamplified) path. Or parallel operation of multiple amplifiers, or of an amplifier and a direct path, may be used to prevent total signal loss upon amplifier failure.

In the automatic switching method, switching could be done by mechanical means such as an electrically controlled mirror movement. Compensation for coupler power failure could be made fail-safe by requiring that the amplifier be placed in (rather than removed from) the optical path by the operation of the mirror actuator. To sense failure of the amplifier, however, would require comparing the input and output signals of the complete electro-optical amplifier, which would seriously increase the size and complexity of the couplers. Furthermore, the comparison electronics would have their own set of reliability problems.

Parallel operation would seem to be preferable, since it avoids this problem. But the parallel operation of multiple amplifiers would not compensate for coupler power outage. Therefore, the combination of amplified and direct paths appears to be the best choice from the standpoint of reliability, complexity, and cost. The details of such an arrangement are given in appendix B, which shows that a system can have essentially constant signal level if system backscatter is kept low enough.

The degradation of signal level that would accompany failure of a given amplifier essentially equals the system loss for which that amplifier was compensating. Hence the greatest reliability will result from (1) providing the largest possible excess signal margin at

the receivers, (2) maintaining the system loss as low as is consistent with state of the art and cost, and (3) subdividing the bus into as many amplifier/system-loss units as is consistent with the limitations of cost and system complexity.

Because minimum system loss is desirable, single-fiber cable is the preferred transmission medium. Though the active tee coupler technique described in appendix B is based on the use of bundle technology, the same principles can be applied in the single-fiber coupler techniques described in appendix A. Fiber junctions of the type described there will probably be quite directional, having a small ratio of back directed to forward directed components of the coupled signal. During the preparation of this study, Pan[20] reported the fabrication of single-fiber couplers having directivities greater than 21.6 dB. Therefore, single-fiber junctions of this type should be acceptable substitutes for the beam splitters used in appendix B.

Figure 19 shows how signal amplification could be incorporated in a low loss single-fiber coupler. The amplifier units, labeled G, each consist of a photodiode, preamplifier, LED driver, and LED. Separate amplifiers handle signals in opposite directions on the bus. Before the bus signal reaches the passive coupler, it is sampled by a sampling coupler, labeled K_1 in the figure. It is then amplified, and a portion is added to the bus signal emerging from the passive coupler by the output coupler, labeled K_2 in the figure. The loop, d, in the bus is added to equalize the delays of the direct and amplified signals so that any differential delay, which would result in partial phase cancellation of the SDMS subcarriers, is small compared with the few-nanosecond period of the highest frequency subcarrier.

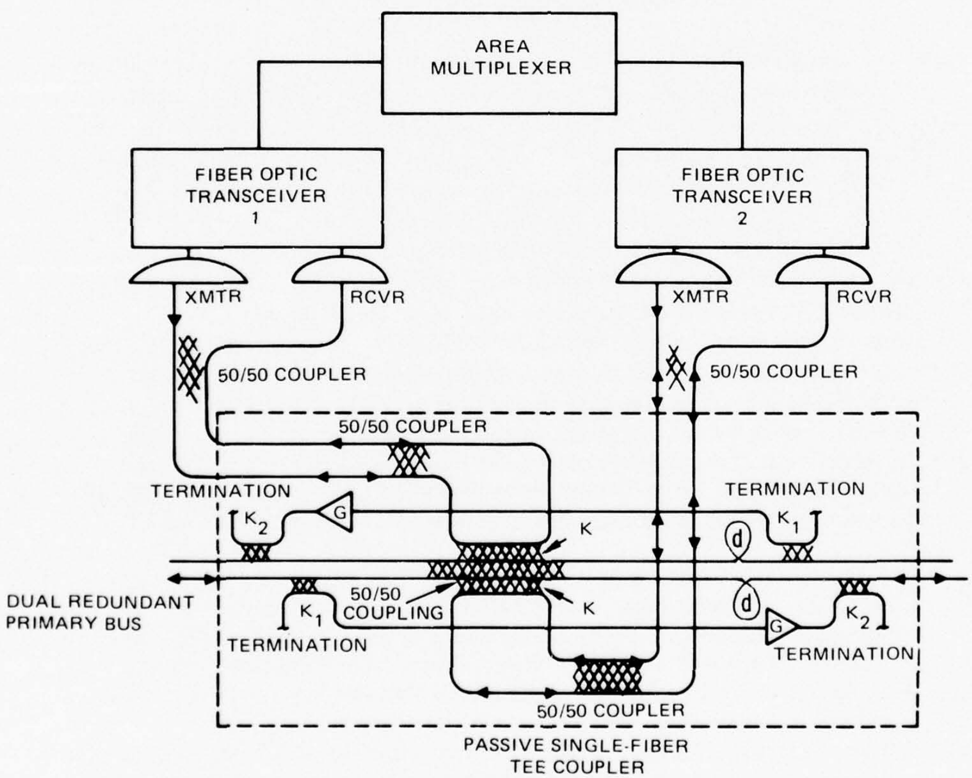

Figure 19. Low loss single-fiber coupler with amplification to compensate for loss.

Figure 20 shows an alternative bus structure that could be attractive from a maintenance standpoint. Because the active couplers permit the acceptance of added loss, the bus couplers are incorporated with the transceivers at each area multiplexer. Presumably, the area multiplexer area is readily accessible to maintenance personnel, unlike positions that might be designated for electrical tee couplers. Each transceiver-coupler unit, labeled TR/C in the figure, would, as before, contain separate transceiver and coupler units for the two area multiplexer halves. A disadvantage of this configuration is that the added cable loss would make the system somewhat more sensitive to the effects of amplifier failure. Worse still, battle damage would have greater impact: in addition to added vulnerability resulting from the greater cable lengths required, all of the primary busses converge at each area multiplexer, where a single battle impact could sever all of the busses at once and leave the entire system inoperative. The tradeoff between these advantages and disadvantages depends largely on the particular installation.

Probably the matter of greatest uncertainty related to the use of active couplers with SDMS is the problem of intermodulation distortion associated with modulation of the LED. Curvature of the power-output versus current-input characteristic of the LED can lead to the generation of subcarrier harmonics and intermodulation products. Harmonics of the subcarriers all lie above the operating band and hence are of no consequence. Likewise, the second order intermodulation products (sum and difference frequencies) lie outside the operating band. Third order difference terms (such as $2f_1 - f_2$) do lie within the operating band, however, and will cause interference if they are strong enough. In measurements of intermodulation distortion generated by a Burrus LED, Ozeki and Hara[23] found third order intermodulation components 60 to 75 dB below the fundamental. As shown earlier in this study, the minimum acceptable signal at the SDMS receiver input is about 13 dB above the noise level. If the losses throughout the system are truly compensated by active couplers, all individual signals assume this level. The maximum total signal present at the receiver input is the sum of five such signals (see table 1) – 7 dB above the level of one signal or 20 dB above the input noise level. Third order intermodulation products of some 60 dB below the fundamental are thus some 40 dB below the SDMS receiver noise level, as illustrated in figure 21, and should be of little concern.

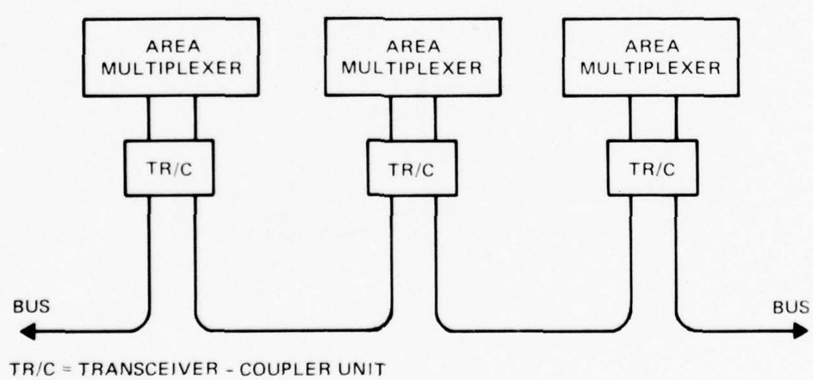

Figure 20. Active tee coupler bus configuration with all components at area multiplexers.

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[23]Ozeki, T, and Hara, EH, Measurement of Nonlinear Distortion in Light Emitting Diodes, Electronics Letters, vol 12, no 3, 5 Feb 1976

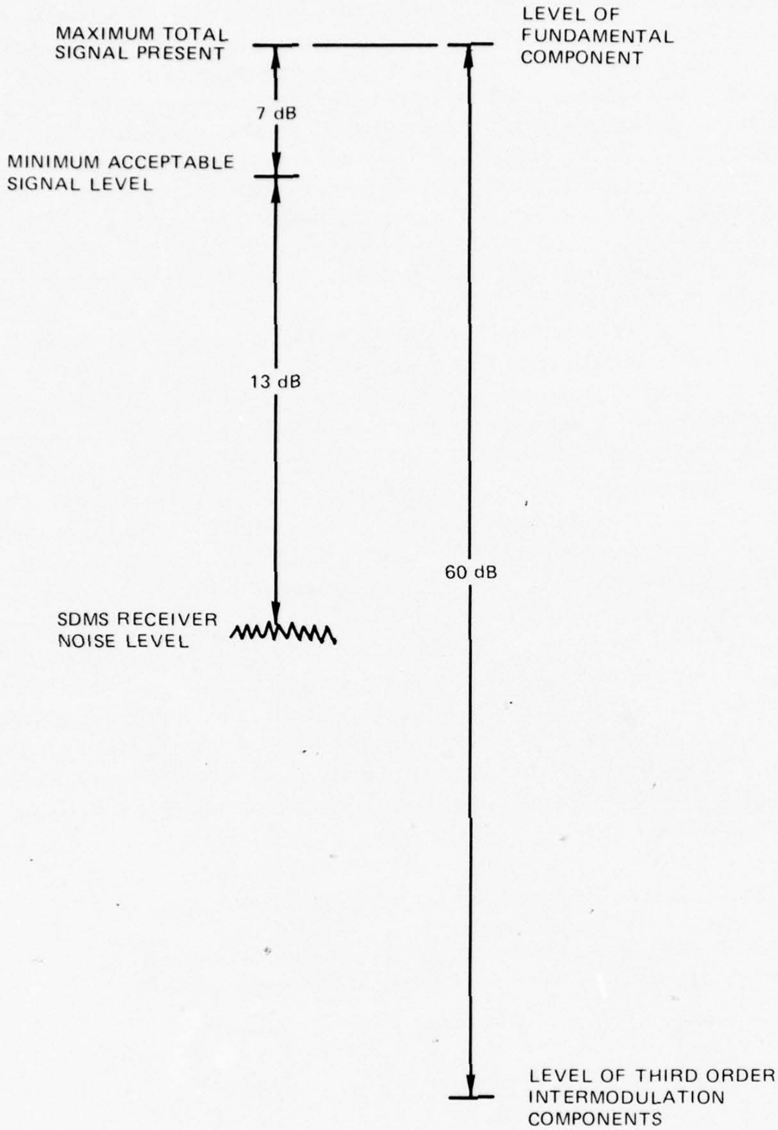

Figure 21. Comparison of receiver dynamic range and third order intermodulation product level.

CONCLUSION

Conversion of the SDMS primary bus to use the fiber optic transmission medium is feasible for both the maximum and nominal size systems. The latter can use any of the three system configurations considered — the passive tee, passive star, and fail-safe active tee. Of these, the passive tee is preferred because it is the simplest and uses the least amount of cable. For the maximum size SDMS, the passive tee configuration seems feasible on the basis of the small amount of experimental evidence that can be cited. The passive star and fail-safe active tee configurations provide workable but less satisfactory alternatives.

RECOMMENDED BUS CONFIGURATION

Table 3 summarizes the recommendations stemming from this study. The configurations shown in the first column would satisfy the requirements of a low risk, low cost development program, whereas those in the second column would apply to a higher risk, more thoroughgoing, and hence higher cost program. Recommendations are shown for both the maximum size and the nominal size SDMS.

The passive tee coupler bus using single-fiber cable is the preferred system configuration from the standpoint of cable cost and conformance to the basic SDMS cabling arrangement. It is feasible without qualification for the nominal size SDMS, but its feasibility for the maximum size SDMS depends on how far coupler excess losses can be reduced. The results of the limited amount of experimental data published so far (see appendix D) indicate that total excess loss per coupler can probably be reduced to about 1 dB, a value that would allow construction of a system that could accommodate up to 12 area multiplexers. Because of the dearth of effort in this area, however, further development effort may yield considerable improvement. Therefore, the recommended and most logical approach is first to build a nominal size system and then from the experience gained to reassess the feasibility of reducing the coupler excess loss to the 0.6 dB value required for the maximum size system. On the other hand, if a shorter development time and the lowest possible risk are required, a star coupler configuration with a multifiber-cable trunk is recommended for the maximum size SDMS.

TABLE 3. RECOMMENDED BUS CONFIGURATIONS.

SDMS size	Development risk	
	Low	Medium
Nominal	Passive tee coupler	Passive tee coupler
Maximum	Passive star coupler	Passive tee coupler

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23. Ozeki, T, and Hara, EH, Measurement of Nonlinear Distortion in Light Emitting Diodes, Electronics Letters, vol 12, no 3, 5 February 1976.

APPENDIX A
LOW LOSS SINGLE-FIBER TEE COUPLER

The fiber optic tee coupler is the optical equivalent of the microwave directional coupler. It usually serves to couple a fraction, K, of the available power between a fiber optic bus and some external device. For equivalent angular and spatial power distributions, the coupling factor, K, applies for either direction of power transfer. The ideal coupler taps from the bus only that power which it delivers to the cable feeding the external device. However, additional power losses can be expected to occur at any discontinuities within a coupler such as can result from lack of precise mechanical fit and alignment at junctions required for the introduction of mirrors, mixing blocks, etc. The efficiency obtainable from a given coupler design depends largely on the degree to which the dimensional tolerances it requires can be met.

When the internal mirror, mixing block coupler technology developed for use with fiber optic bundles is extended to single fibers, the precision requirement on dimensional tolerances increases by about an order of magnitude. This increase is occasioned by the minute size of usable fibers (1-10 mils diameter), and it is difficult and expensive to implement.

Several arrangements for decreasing the required mechanical precision by magnifying the light beam have been proposed.[A1, A2] These have depended, for beam magnification, on both index gradient and index discontinuity types of lenses, as well as on tapered fiber sections. Losses accompanying the magnification and demagnification, however, place a limit on the efficiency that can be expected from such arrangements.

An alternative method that might be used to provide coupling between single fibers consists of first securing each fiber to the periphery of a mandrel several inches in diameter. A flat of controlled area is then ground on the resultant toroidal surface of each fiber of sufficient depth to expose the fiber core. Superposition of the flat areas, with or without index matching material, provides the desired coupling. Where the cladding is absent, the field from one fiber core extends into the other – those rays in the first fiber which are directed toward the surface area without cladding pass into the second fiber. This appears to be a practicable arrangement. The only problems would seem to be the requirement for accurately grinding, polishing and superimposing the flats and the necessity for curving the fibers, which could result in some added loss.*

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*Several other arrangements for either tapping light from or providing coupling between single fibers have been reported. Muska[A3] describes a method of tapping a plastic clad fiber by removing the plastic cladding and clamping the core in contact with a piece of soft plastic which in turn is in contact with a photodiode. Pan[A4] describes three methods of obtaining directional coupling between single fibers. In the first, the coupling is provided by interaction between the evanescent fields of a pair of bent clad fibers in contact at a point in the periphery of the bend. In the second, coupling is provided by removal of the cladding at the point of intersection of a pair of fibers crossed at a properly chosen angle. This method appears to be analogous to the Bethe-hole coupler of microwave technology. The third is quite similar to the method described here in that coupling is provided by partially etching off the cladding at a series of points between a pair of parallel fibers, and then filling the etched volume with index matching fluid.

[A1] WM Caton, Patent Disclosure, Navy Case Number 58290, 24 Dec 1975

[A2] DJ Albares, AL Lewis, and LB Stotts, Patent Disclosure, Navy Case Number 60536, 27 Jan 1976

[A3] WM Muska, Detector Taps for Single-Fiber Optical Data Bus, Topical Meeting on Optical Fiber Transmission, January 7-9, 1975, Williamsburg, Virginia, sponsored by OSA and IEEE

[A4] JJ Pan, Fiber Optic Directional Coupler, Conference on Laser and Electro-Optical Systems, 25-27 May 1976, San Diego, California, sponsored by OSA and IEEE

The coupling method proposed here avoids the requirement for and expense of the aforementioned operations, and hence should allow the construction of a satisfactory coupler at reduced cost. In its simplest form, the method is illustrated in figure A1. Here we see two unclad fibers, B and C, such as would result from stripping the plastic cladding from a portion of a pair of plastic-clad fused silica fibers, in contact and approximately parallel. Radiation does not penetrate the sides of the fibers, because the refractive index of the air surrounding the fiber is even lower than that of the plastic cladding. The two fibers are joined by a patch of transparent cement, D, having a refractive index roughly matching that of the fibers.

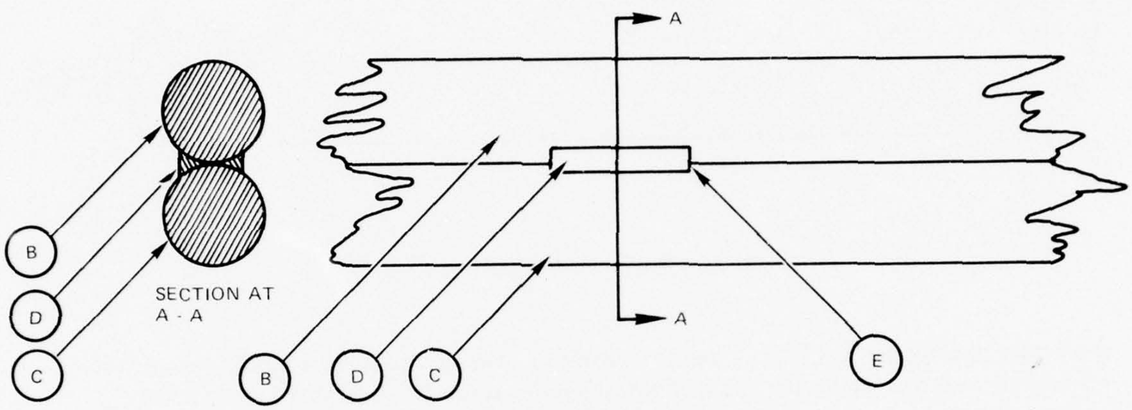

Figure A1. Coupling between unclad fibers.

As is illustrated in figure A2, power transfer between the fibers occurs when light rays which would have been totally reflected from the air-to-fiber interface are only *partially reflected from the cement-to-fiber interface.* Most of the remainder passes on into the second fiber. Since some reflection also occurs at the cement-to-second-fiber interface, and since most of this light will be lost due to its direction, most efficient coupling results when the index of the cement equals that of the fibers.

The coupling factor is a function of the surface area made common to both fibers by the cement patch, ie, of the length and fractional circumference covered by the cement.

As with most fiber optic tee couplers, the fraction of the incident power coupled to the second fiber is dependent on the spatial and angular power distribution in the first fiber. For a given incident power distribution, the coupled power should increase linearly with the common area until a significant fraction is coupled to the second fiber. Beyond this point the coupling factor becomes less dependent on area (as a result of power coupled back from the second fiber), becoming independent of it when the incident power is split equally between the two output fibers.

Thus, it is apparent that an "oversize" coupling area can be used to equalize the power level between two or more fibers carrying the same signal in parallel as, for instance, might be required to provide transmission redundancy in a high reliability system.

Power loss within the cement should be negligible due to the short path involved. We assume, of course, that we can avoid the inclusion of bubbles, scattering particles, and

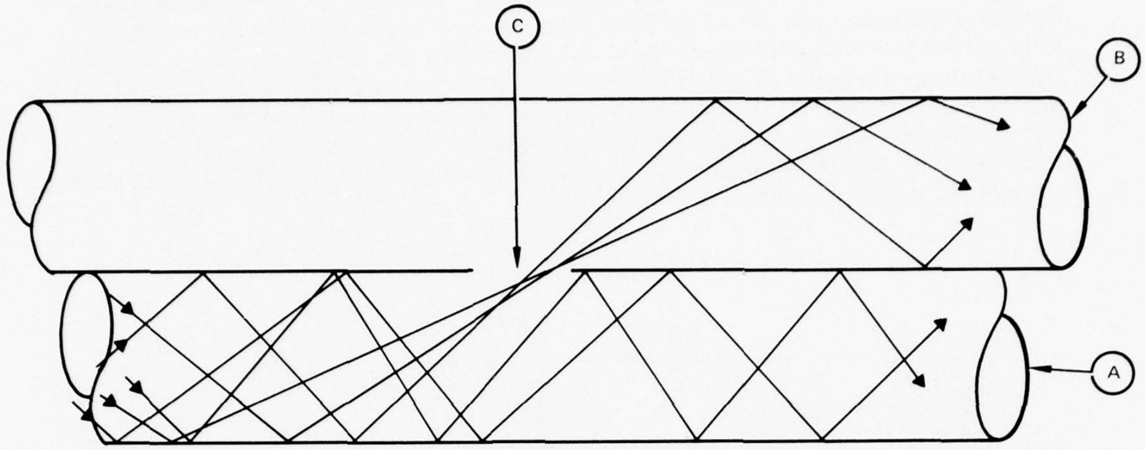

Figure A2. Power transfer between fibers.

molecular absorption bands by a careful choice of cement. Surface irregularities on the cement-air interface along the sides of the fiber can result in scattering loss, but the surface tension of the cement should smooth the surface sufficiently to make this loss negligible.

The cement-air interface at the end of the cement path (E in figure A1) will, on the other hand, result in some unavoidable power loss because the light tends to strike it at too small angles of incidence. While suitably shaping this end face can decrease this loss to some degree, it is desirable to keep the end area as small as possible relative to the fiber cross section. Minimizing the amount of fiber circumference covered by the cement will also minimize the end area. The amount of fiber surface area covered can still be made as large as desired by extending the area along the fiber.

Figure A3 shows the loss factors to be expected from several patterns of two, three, and four cemented fibers. The loss factors were calculated on the assumption that all light reaching the end face of the cement volume is lost. Each loss factor is, therefore, the ratio of the area occupied by the fiber cross section to the total area of the figure. In patterns E through L, the cement is bounded by circular and plane surfaces such as might be producible by simple molding techniques. Lower end losses, however, result from the preferred configurations A through D. In patterns B, C, and D, the cement used for coupling is contained in the volume bounded by the fibers. In pattern A, the cement is bounded by a cylindrical surface having a radius one-fourth that of the fiber. A cylinder of this radius exactly fits the space between the contacting fibers and a tangent plane; this geometric relationship should simplify the assembly procedure.

A particularly simple method of assembling the preferred configurations would be to obtain the cement in the form of a round thermoplastic fiber of appropriate diameter. The required volume of cement could then be converted to a measured length and placed between the fibers. The assembly would be clamped under moderate pressure and heated until the plastic melts and fills the cavity between the fibers. Among common materials,

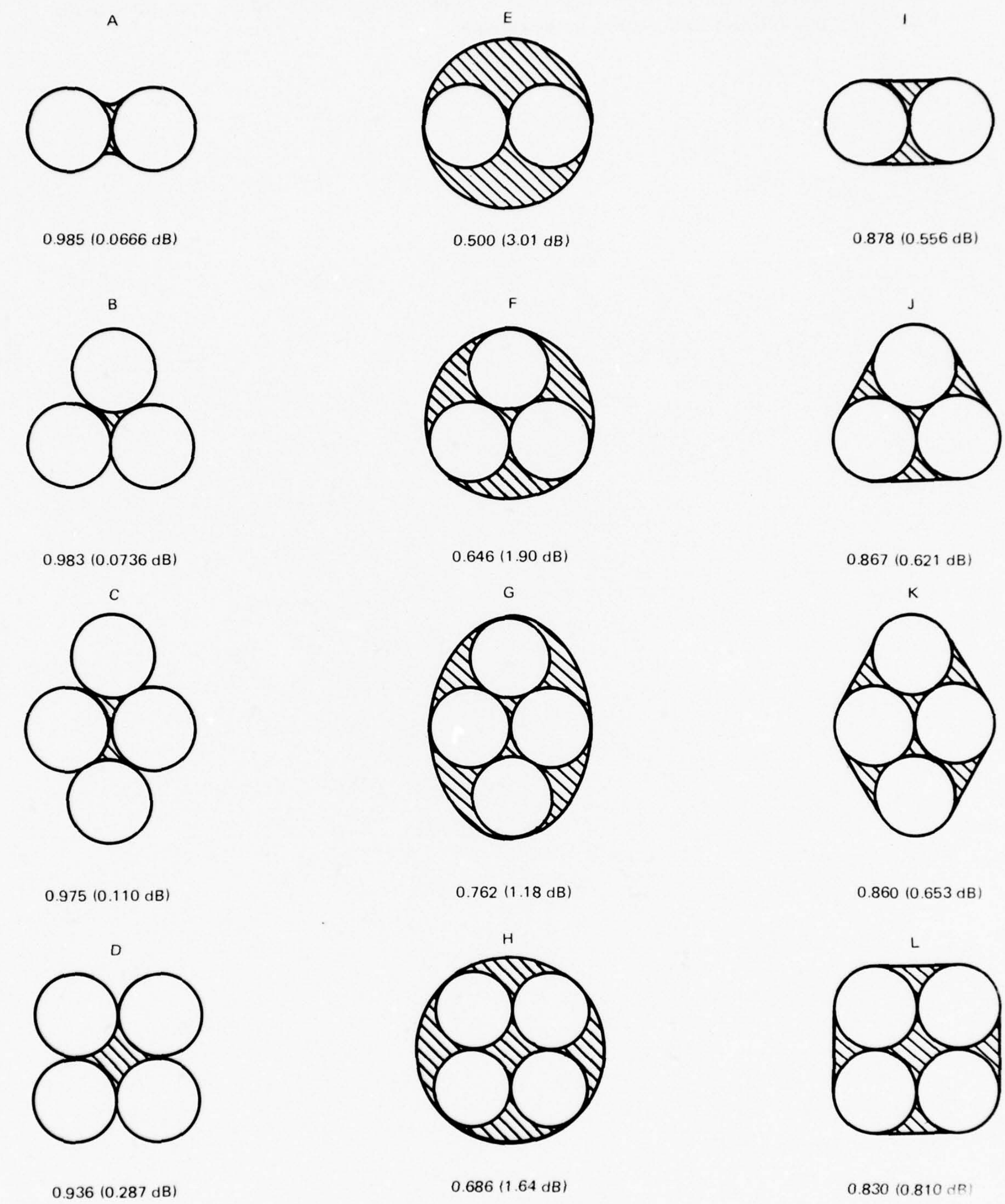

Figure A3. End loss of coupled fiber configurations.

lucite (polymethyl methacrylate) would probably be acceptable. It has an index of about 1.489, compared with 1.456 for fused silica. The various plastic fibers used in weaving cloth are possibilities that should be investigated.

APPENDIX B
FAIL-SAFE ACTIVE TEE COUPLER

As the number of taps on a data bus increases, a point is reached where the end-to-end loss exceeds the capability of the transmitter-receiver combination to overcome it. At this point, additional gain somewhere between the end couplers is required if further bus growth is to be permitted. An amplifier arranged to provide the required signal amplification is referred to as an active device or repeater. The classic objection to the inclusion of repeaters in otherwise passive systems is that the system reliability will thereby be decreased. Failure of the amplifier or its power source will render the entire bus inoperative.

We offer here a basic technique for avoiding this limitation and describe a device configuration capable of implementing it on a fiber optic data bus. For the sake of review, consider the standard repeater arrangement shown in figure B1.

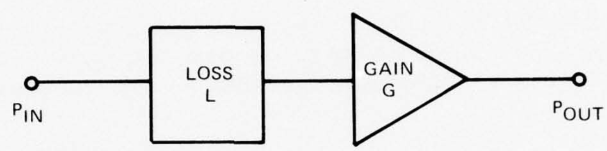

Figure B1. Simple transmission system.

Here we see a transmission system having a loss, L, and an amplifier having a power gain, G. If GL = 1, the power out will equal the power in and the effect of signal attenuation will be avoided. However, in the event that G suddenly becomes zero, the transmission loss becomes infinite.

In figure B2 we see a similar transmission system, but this time the amplifier is arranged to parallel a portion of the transmission system of loss, a. The beam splitters have coupling factors f_i and f_o. If B_i and B_o are total backscatter ratio at input and output respectively (sum of backscatter from beam splitter and subsequent fiber optics), the system will remain stable as long as $(G\ f_o\ B_o\ a\ B_i\ f_i) < 1$. In general we must depend upon control of B_o and B_i to maintain stability. The power output of the system is $P_{out} = P_{in}\ L\left[f_i\ f_o\ G + (1 - f_i)(1 - f_o)a\right]$. For a perfectly compensated system, $P_{out} = P_{in}$, from which the required gain

$$G = \frac{1}{Lf_if_o} - \frac{(1 - f_i)(1 - f_o)a}{f_if_o}$$

With this arrangement, amplifier failure reduces the signal by the factor $La(1 - f_o)(1 - f_i)$ rather than by infinity. Since the loss, a, will ordinarily be quite small, and f_i and f_o can be made as small as we like by corresponding increases in the gain and power output of the amplifier, the signal loss factor upon amplifier failure can be made essentially equal to L. L can, in turn, be made as small as we desire by subdividing the system and correspondingly increasing the number of repeaters used.

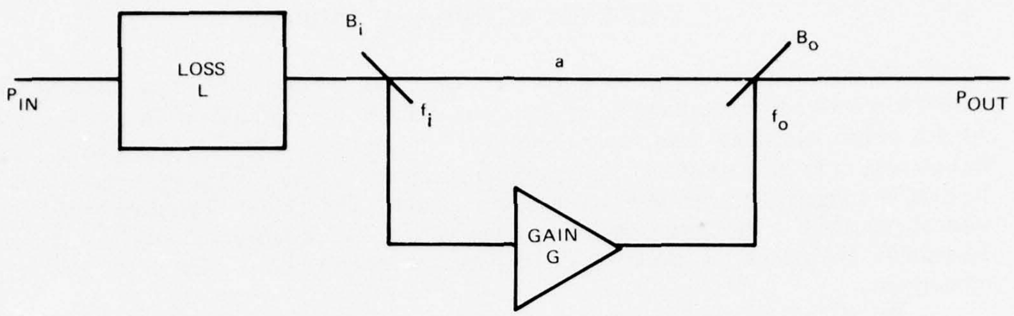

Figure B2. Parallel path transmission system.

The power output, P_a, required from the amplifier for a given system power level, P_{in}, is equal to the system power loss to be compensated, $P_{in}[1 - (1 - f_o)(1 - f_i)aL]$, increased by the output beam splitter loss, f_o. Thus the required power

$$P_a = \frac{P_{in}}{f_o}\,[1 - (1 - f_o)(1 - f_i)aL].$$

For a typical system power level of 10^{-4} watts, an attenuation, aL, of 0.5, and a reflectivity of 10 percent for both beam splitters, an amplifier output capability of 0.6 mW would be required.

Extension of this concept to bidirectional operation is illustrated in figure B3. Here right- and left-directed signals are amplified by separate amplifiers having power gains G_R and G_L respectively. Transmission loss factors to the left and right of the repeaters are L_L and L_R respectively. For signals directed to the right, L_L is compensated for by G_R, and L_R is compensated for by the next repeater to the right. Similarly, for left-directed signals the loss L_R is compensated for by G_L; and L_L is compensated for by the next repeater to the left. With each of the beam splitters, M_1, M_2, M_3 and M_4, is associated a coupling fraction f_n and a backscatter factor B_n. In addition, the left- and right-hand transmission media have backscatter factors B_L and B_R, respectively. System stability requires that the loop gains around each of the three feedback loops in the system be less than unity. Thus in the case of the upper loop we require that

$$G_L a(1 - f_2)\left\{B_4 + f_4(1 - f_4)\left[B_1 + (1 - f_1)^2 B_L\right]\left[B_3 + f_3(1 - f_3)B_R\right]\right\} < 1.$$

In the case of the lower loop,

$$G_R a(1 - f_4)\left\{B_2 + f_2(1 - f_2)\left[B_3 + (1 - f_3)^2 B_R\right]\left[B_1 + f_1(1 - f_1)B_L\right]\right\} < 1.$$

An in the case of the outside loop,

$$G_L G_R f_2 f_4\left[B_1 + f_1(1 - f_1)B_L\right]\left[B_3 + f_3(1 - f_3)B_R\right] < 1.$$

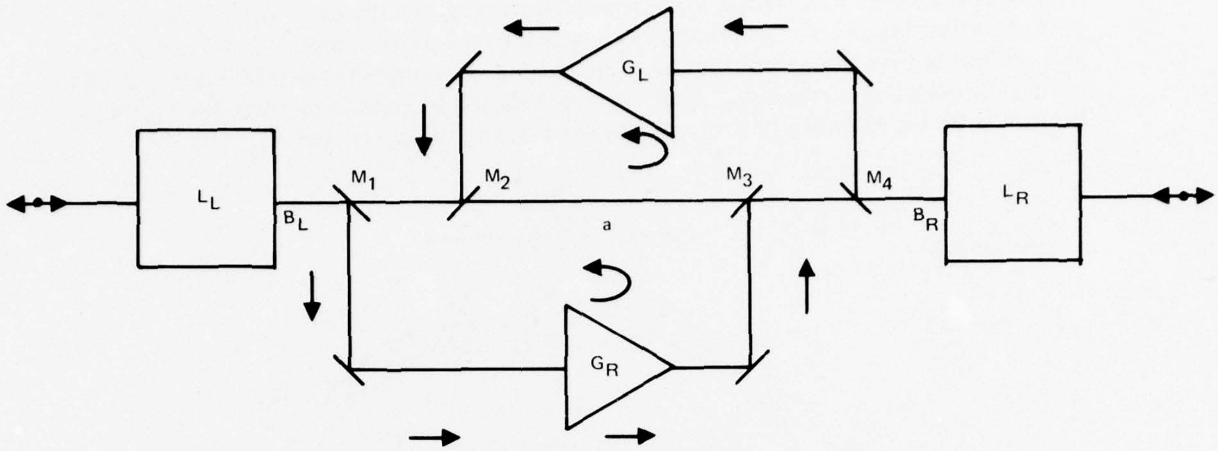

Figure B3. Bidirectional parallel path transmission system.

Since each of the above expressions contains backscatter, B, as a factor, whatever gain is needed for loss compensation will be permitted if the backscatter can be sufficiently reduced. The gains required for complete compensation are

$$G_L = \frac{1 - L_L a(1 - f_1)(1 - f_2)(1 - f_3)(1 - f_4)}{L_i f_1 f_3 (1 - f_4)}$$

and

$$G_R = \frac{1 - L_R a(1 - f_1)(1 - f_2)(1 - f_3)(1 - f_4)}{L_R f_4 f_2 (1 - f_1)}$$

In applying this concept, the following qualifications must be considered:

1) The time delays of the two parallel transmission circuits must be matched to within a small fraction of the data or subcarrier period as the case may be.

2) The method actually used for combining the direct and amplified signals must provide a high directivity so as to minimize backscatter and must have a reasonably low power loss.

3) Backscatter in the adjacent transmission system must also be minimized.

Figure B4 shows a bidirectional repeater based on the foregoing concept. Power division is accomplished by division of the fiber bundle at S. A portion of the signal coming from the mixing block, M, at the left is separated from the main channel by bundle division at S, is amplified by the photodiode, amplifier, driver and LED combination, G, after which

a fraction is coupled back into the mixing block, M, at the right. Signals traveling to the left follow the upper path in similar fashion. A delay loop, D, is provided in the main channel to equalize the time delays in the three channels. The amplifier time delay is a function of the device rise times, lead propagation times, and the delay of any equalizing circuits in the amplifiers. The mixing block serves to spread the amplified and direct signals uniformly over the output bundle. Since backscatter limits the usable stable gain of the device, the coupling surfaces of the mixing block should be treated to minimize Fresnel reflection with, for example, index matching fluid or antireflection coating.

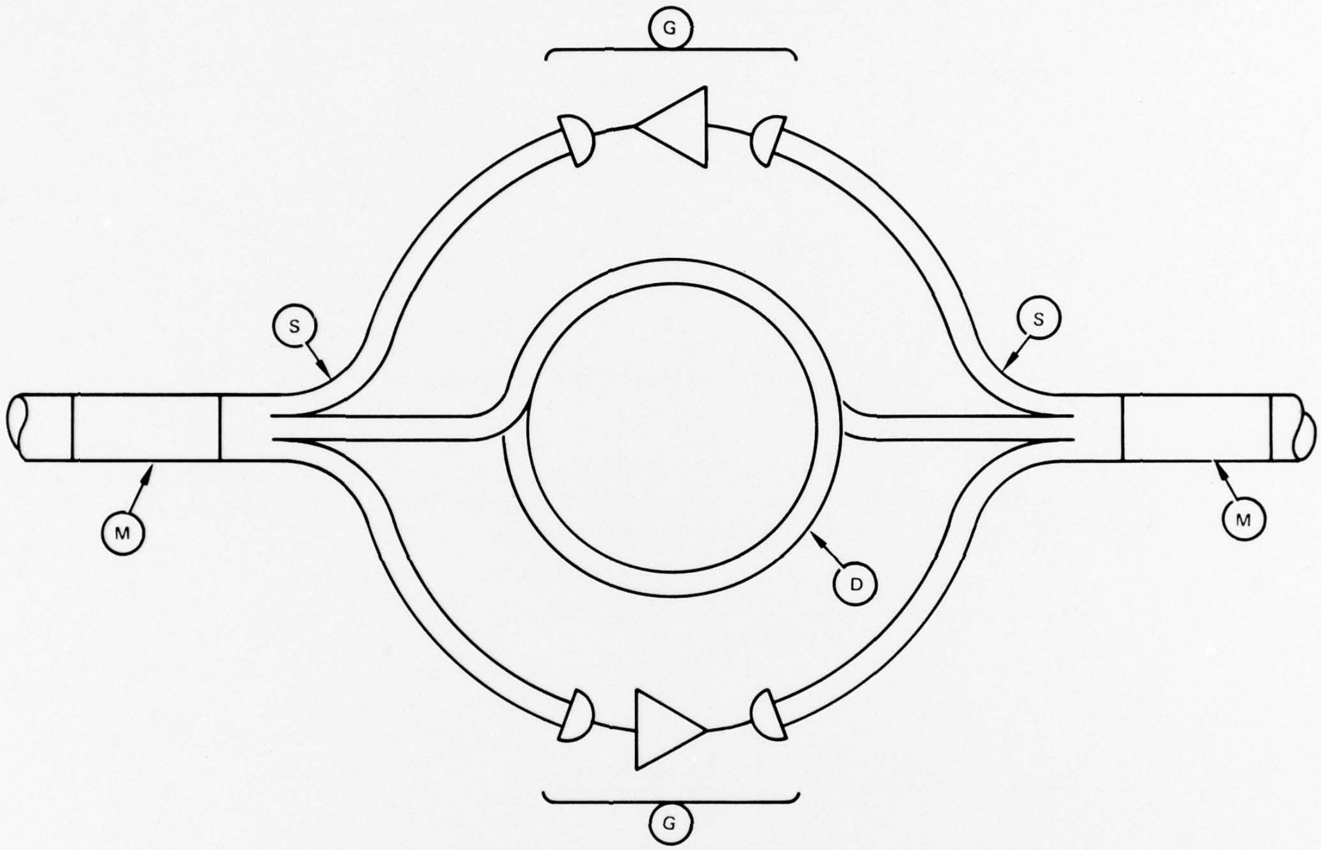

Figure B4. Bidirectional fail-safe repeater.

Figure B5 shows one way of applying the foregoing concept to the requirements of SDMS. In this case it is most convenient to combine the amplification function with the tee coupler function at each of the dual taps on the primary bus. This design is the same as the one previously described except that a dual internal mirror mixing block, C, is inserted at the center of the delay loop, where it provides coupling between the area multiplexer stubs and the primary bus. Placing it at this symmetrically located point in the repeater provides the same time delay and signal amplitude for both directions of transmission. T_1 and T_2 designate the fiber optic cables leading to the area multiplexers. The other designations are the same as in the previous example.

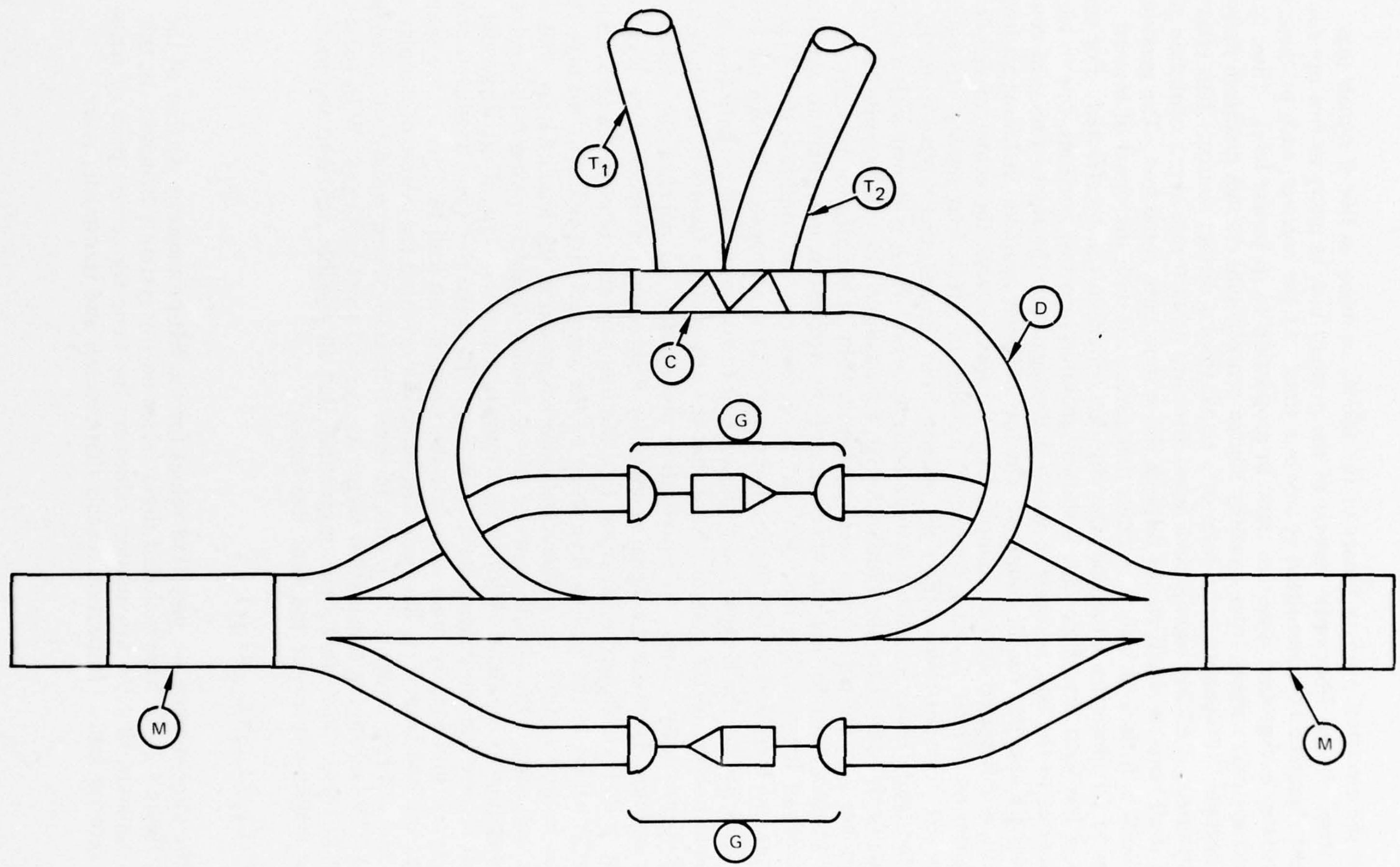

Figure B5. Fail-safe active tee coupler.

APPENDIX C
EQUALIZATION OF BUS SIGNAL LEVELS

On the electrical primary busses of the SDMS, as many as five rf signals may exist at a time. In the fiber optic version of the primary bus, as many as five optical signals must therefore be transmitted at any one time. At the receiver, each of these signals contributes background quantum noise in proportion to its power level. Thus, in an unequalized system, a signal from a nearby source can generate enough quantum noise to seriously degrade the signal-to-noise ratio of a signal from a distant source. This effect will be minimized if all five signals have equal intensity at each receiver, a condition that will result if all possible signal routes through the system have equal loss. The maximum quantum noise will then be only five times that associated with the signal of interest.

Figure C1 illustrates a method whereby this condition can be effected. For simplification, a bus with five single taps is shown separated into two portions, one in which light propagates to the left, and one in which it propagates to the right. Identical coupling factors are assumed for all couplers. The loss between couplers, including all loss within them, is designated as, for example, L_{12}, for loss between the center of coupler 1 and the center of coupler 2. Each transceiver handles, in effect, four signals: transmit toward the left, transmit toward the right, receive from the left, and receive from the right. In the figure these are shown as four separate leads. Each is shown with a separate attenuator designated by the symbol A_{T2R}, for example, for the transmit lead of coupler number 2 in the part of the system wherein light propagates to the right.

We proceed next to find the values that these attenuators must have to equalize the path losses of the complete bus. We start by considering the condition that T_{1R} is transmitting, and R_{5R} is receiving the resultant signal, as it propagates through the bus to the right. This path is the longest and highest-loss (prior to equalization) path through the right-hand portion of the system. Note that the attenuation factors in the leads to T_{1R} and R_{5R} are unity. Thus, the equalization process does not increase the end-to-end loss of the system. To make the signal received by R_{4R} equal that received by R_{5R}, the attenuation in its lead, A_{R4R}, must equal L_{45} the loss between couplers 4 and 5. Similarly, the attenuation in the lead to R_{3R} must be the product $(L_{45})(L_{34})$. We may continue in this fashion to find the attenuation factors required in the lead of R_{2R}, and, if the system were larger, the requirements of any remaining receivers arranged to receive power propagating to the right. With these attenuation factors, R_{2R}, R_{3R}, R_{4R}, and R_{5R} will all receive the same signal level from T_{1R}. To make this same condition hold when T_{2R} is transmitting, we must attenuate the signal in the lead to T_{2R} by the same amount that the one from T_{1R} has been attenuated in reaching the center of coupler 2. Hence, we make A_{T2R} equal to L_{12}, and, in similar fashion, A_{T3R} equal to the product $(L_{12})(L_{23})$. The remaining attenuation factor $A_{T4R} = (L_{12})(L_{23})(L_{34})$. With these attenuation factors, it is evident, upon inspection, that all possible right-directed paths through the system experience the same loss factor:

$$L = (L_{12})(L_{23})(L_{34})(L_{45}).$$

In the same manner we may find values for the left-propagating portion of the system. In figure C2, we have included these values on the system schematic. In this figure, it is apparent that the attenuation values are the same for certain pairs of transmitter and receiver leads. Inspection reveals that receiver and transmitter pairs

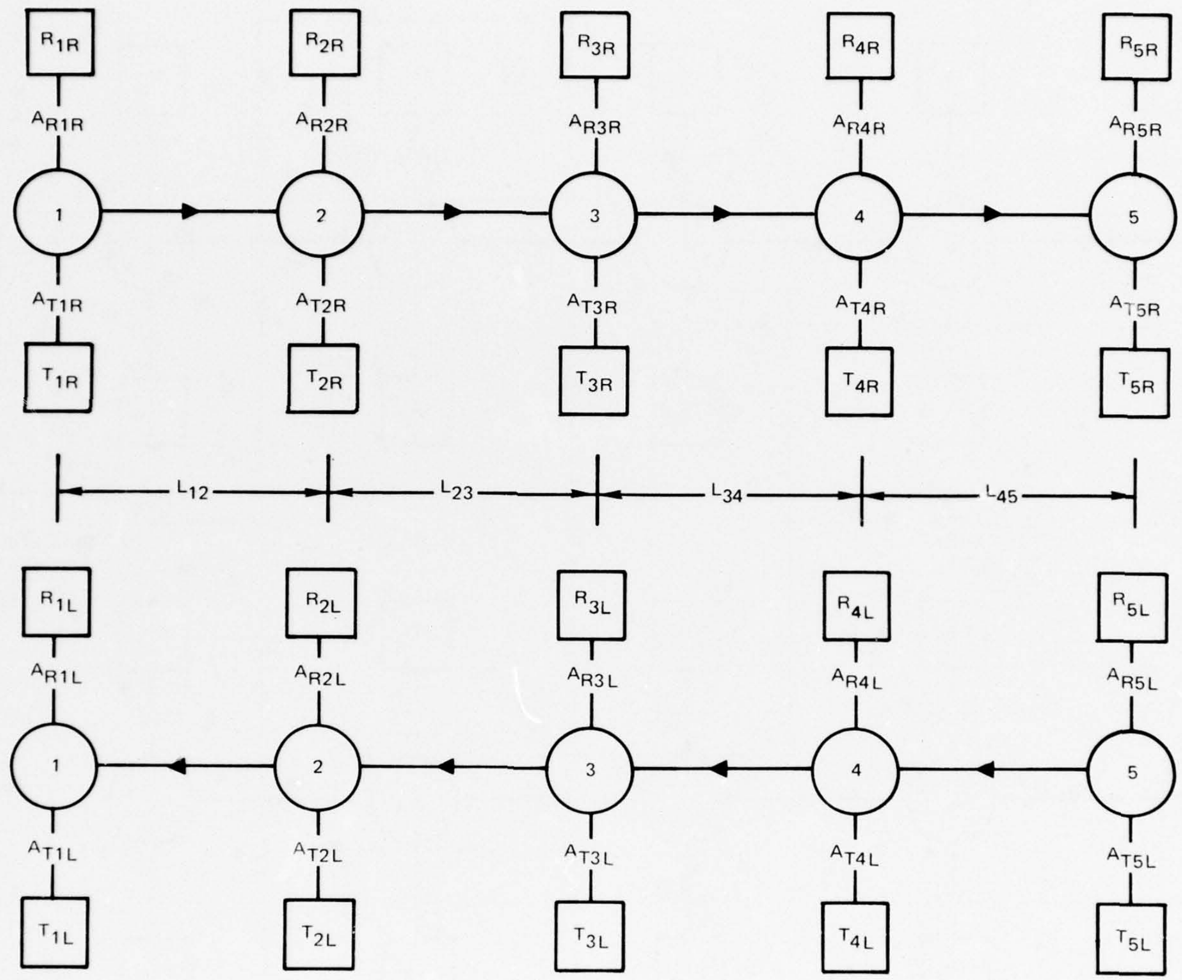

Figure C1. Five-coupler bus with right- and left-hand propagation shown separately.

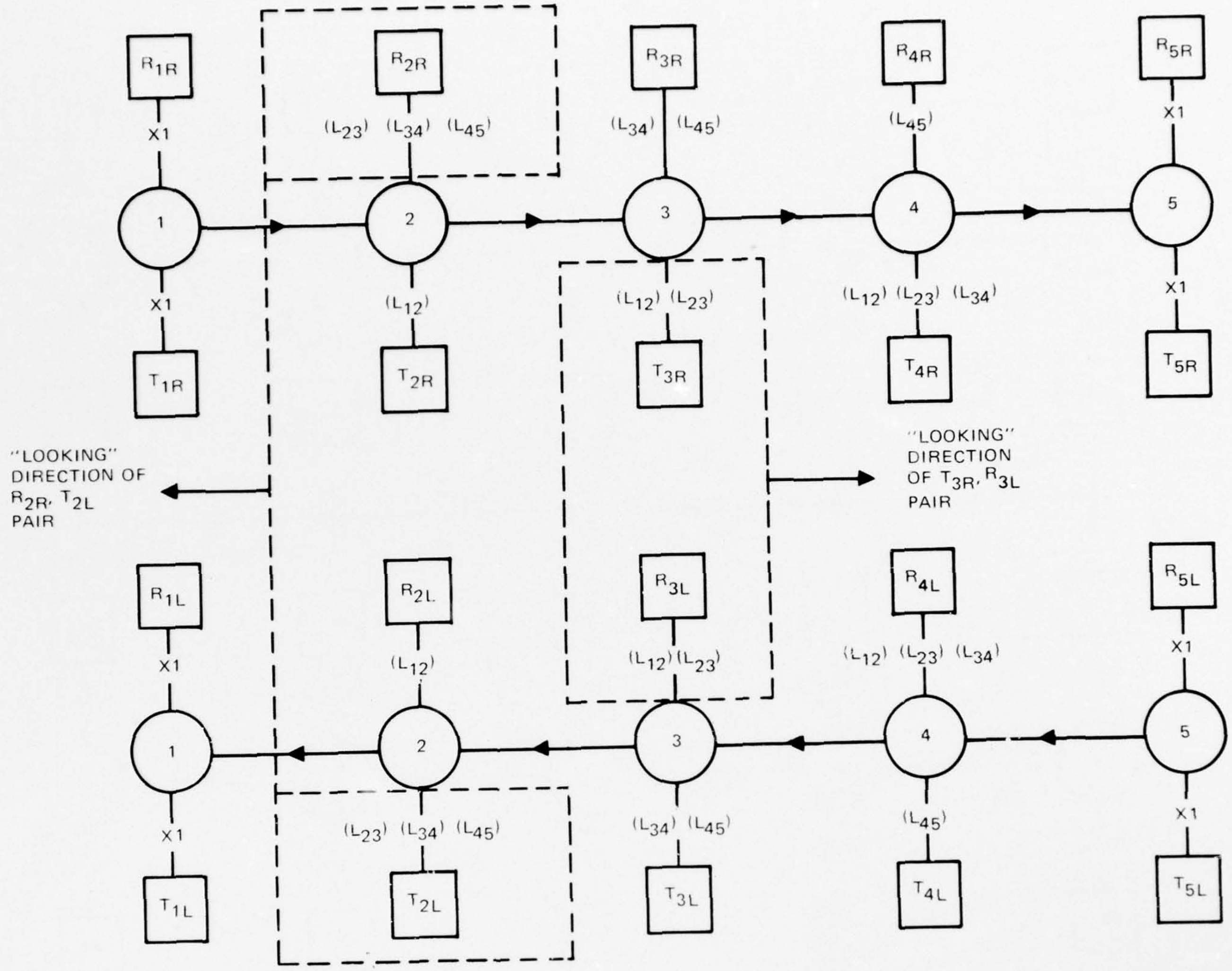

Figure C2. Five-coupler bus showing equalization attenuator values separately for right- and left-hand propagation.

"looking"* in a particular direction require the same attenuation factors. Therefore, we may combine the right- and left-directed systems on the same bus as long as we arrange to have the loss factors in the right- and left-looking leads to a particular transceiver independently adjustable.

It follows from this requirement that the right- and left-looking signals must be kept separate from the point of level adjustment until they are launched in the intended direction on the bus. Several possible ways of making the required attenuation adjustments are illustrated in the following series of figures. These schemes fall into two basic categories: those wherein the attenuation adjustment is done at the transceiver and those wherein it is done at the coupler. Placing the equalization adjustment at the coupler requires only one fiber in the stub connection, while placing it at the transceiver requires two. On the other hand, adjustment at the transceiver may at times be more convenient because of greater accessibility.

In the figures, we illustrate coupling of stubs to the bus by drawing them parallel and in close proximity by analogy to the coupling techniques described in appendix A. For the sake of clarity, we show simple path division—which could have been drawn in the same manner—as a junction of the lines representing the fibers. In the cases where two fibers per stub are required, the fact that these can be enclosed in a common jacket and still meet the independent stubs requirement of SDMS is illustrated by the circle drawn around the pair.

Figure C3 illustrates the simplest equalization scheme. Here we use separate transmitters and receivers for the left- and right-looking functions. The transmitter adjustment is accomplished by variation of the electrical drive to the LED or laser; while the receiver is most easily adjusted by variation of the separation between the fiber and photodiode. At the bus, the stub fibers are connected to opposite ends of the same coupling section so that no additional loss occurs on the bus due to the presence of the two stub fibers. As explained in appendix A, when light couples from the stub to the bus in the parallel fiber coupler, the propagation direction is preserved.

In figure C4, this scheme is modified to require only a single transmitter and receiver by providing adjustable optical coupling between the transmitter and each of its fibers as well as between the receiver and its associated fibers.

In figure C5, the adjustment between left- and right-looking functions is accomplished by a variable second beam splitter, beyond the one that combines the transmitter and receiver paths. Two arrows are drawn to call attention to the requirement that the loss in each lead must be independently adjustable, as opposed to the provision of a simple ratio adjustment.

In figure C6, the left versus right adjustment is accomplished by separate coupling sections on the bus. This arrangement requires only a single stub fiber, but it will result in added bus loss since both sections extract power from the bus. Furthermore, physical means of making a variable adjustment of this type may be difficult to implement.

The scheme illustrated in figure C7 avoids the added loss problem while still permitting the use of a single stub fiber by placing a reflector, M, at the open end of the

---

* By the expression, "looking," we refer to the direction with which the device, or signal route, is concerned—ie, when a transmitter sends power to the right, it is referred to as looking to the right; furthermore, when a receiver accepts power from a source located to the right, it is referred to as looking to the right even though the direction of radiation propagation is to the left. This terminology avoids, at times, some of the semantic difficulties resulting from the fact that the power flow of interest is away from a transmitter, but toward a receiver.

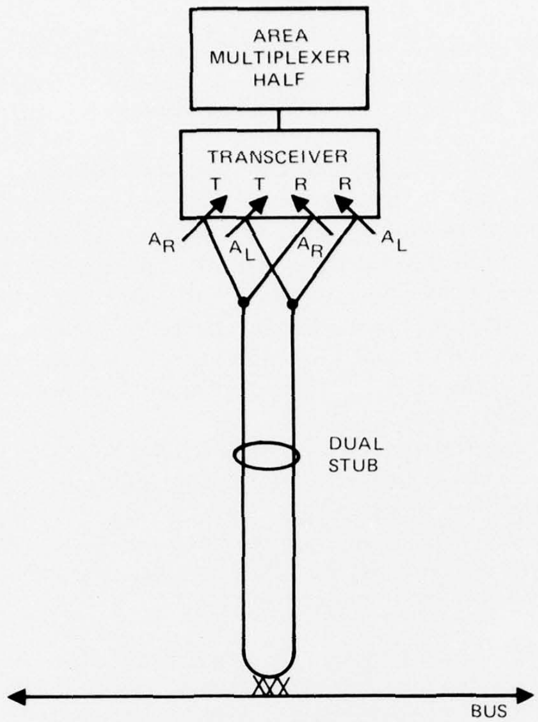

Figure C3. Equalization by means of control of separate transmitters and receivers.

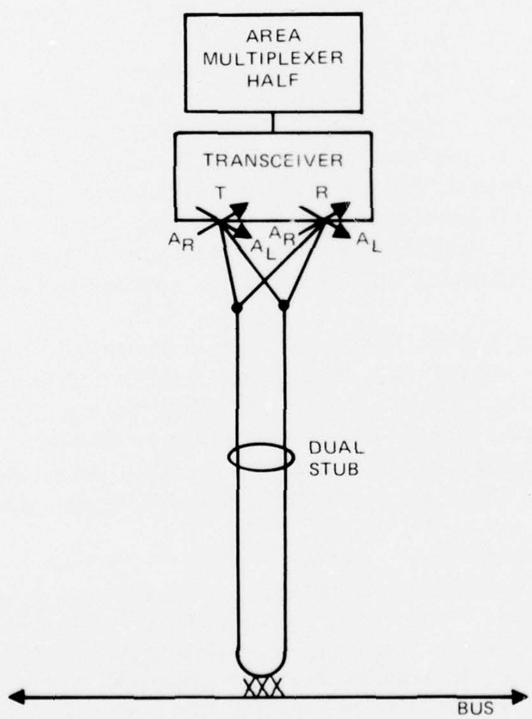

Figure C4. Equalization by separate control of right- and left-looking leads of common transmitter and receiver.

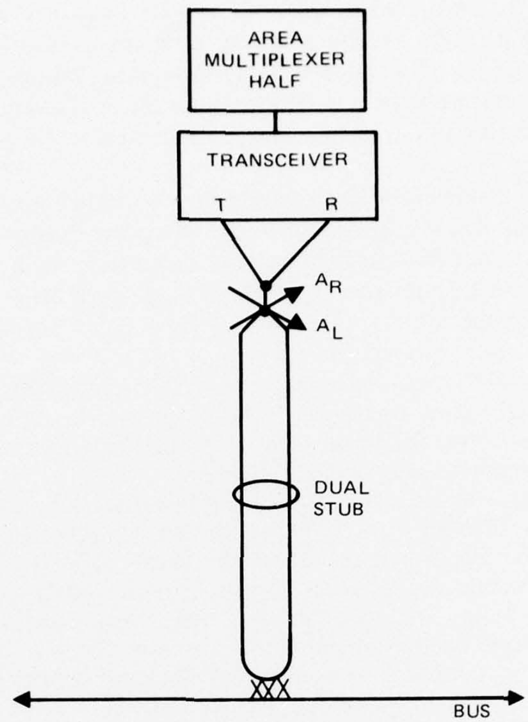

Figure C5. Equalization by separate beam splitters following transmitter-receiver path division.

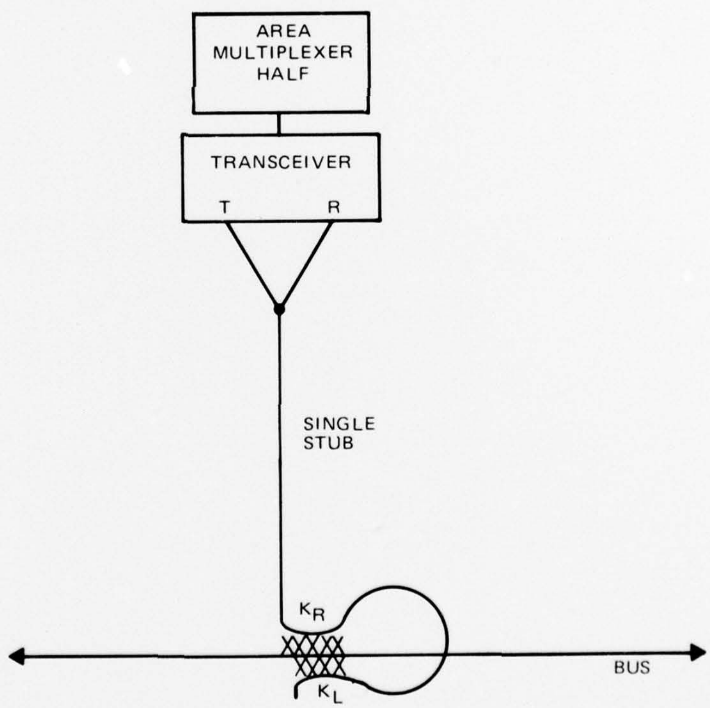

Figure C6. Use of unequal right and left coupling factors to allow equalization with a single stub fiber.

stub. An attenuator, A, interposed in the stub, is used to control the right-looking function, while variation of the efficiency of the reflector is used to control the left-looking function. Variation of the stub-to-reflector spacing would provide a simple means of controlling the reflection efficiency. The orientation of the stub on the bus must be so chosen that the function requiring the most attenuation is the one controlled by the mirror.

In practice, the attenuation levels would be set following system installation in a manner analogous to the one we have used in the foregoing derivation. Transmitter T_{1R}, for example, would be made to transmit, and the signal level at the extreme opposite end of the system, R_{5R}, would be noted. Controls at R_{4R}, R_{3R}, and R_{2R} would then be set to yield that level at the respective receivers. Then, again noting the signal level at R_{5R} with T_{1R} transmitting, attenuators on T_{2R}, T_{3R}, and T_{4R} would be set to yield that same level at R_{5R} with each respective transmitter transmitting instead of T_{1R}. As we have shown in the foregoing derivation, this adjustment—using radiation propagating to the right—will also equalize the left-propagating functions, assuming that all transmitter powers and receiver sensitivities are otherwise equal.

As shown in figure C8, equalization of the signal levels in the star coupler system merely requires equal loss in all stubs. This result can be accomplished by either making all of the stubs the same length and coiling up the excess cable or by placing sufficient additional attenuation in the shorter leads to make them as lossy as the longest one. Installation adjustment would consist of transmitting over any one of the shorter stubs and setting the attenuators on the remaining ones to give the same output signal level as the longest one. Finally, transmission over any of the ones adjusted would permit similar adjustment of the one initially used for the input signal.

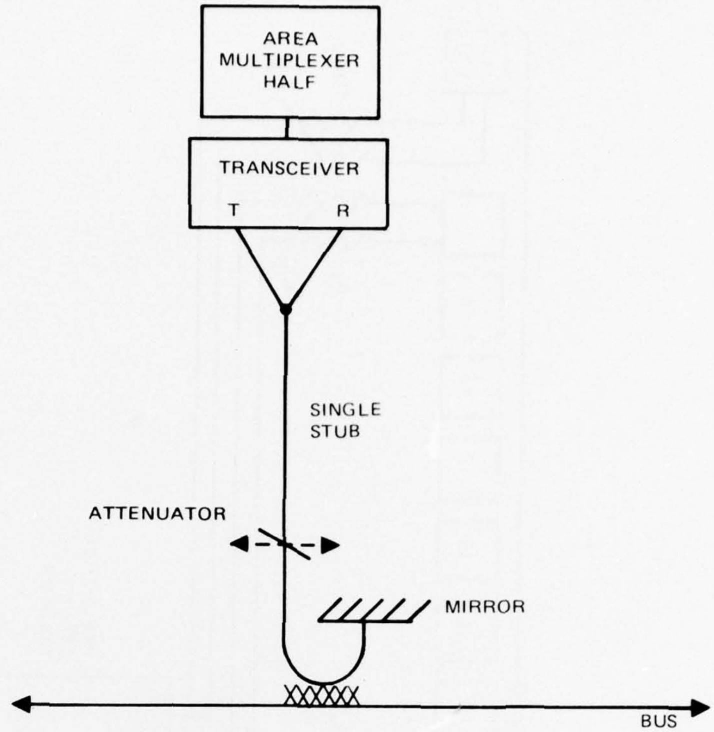

Figure C7. Use of reflective fiber termination to provide unequal right and left coupling factors for equalization with single stub fiber.

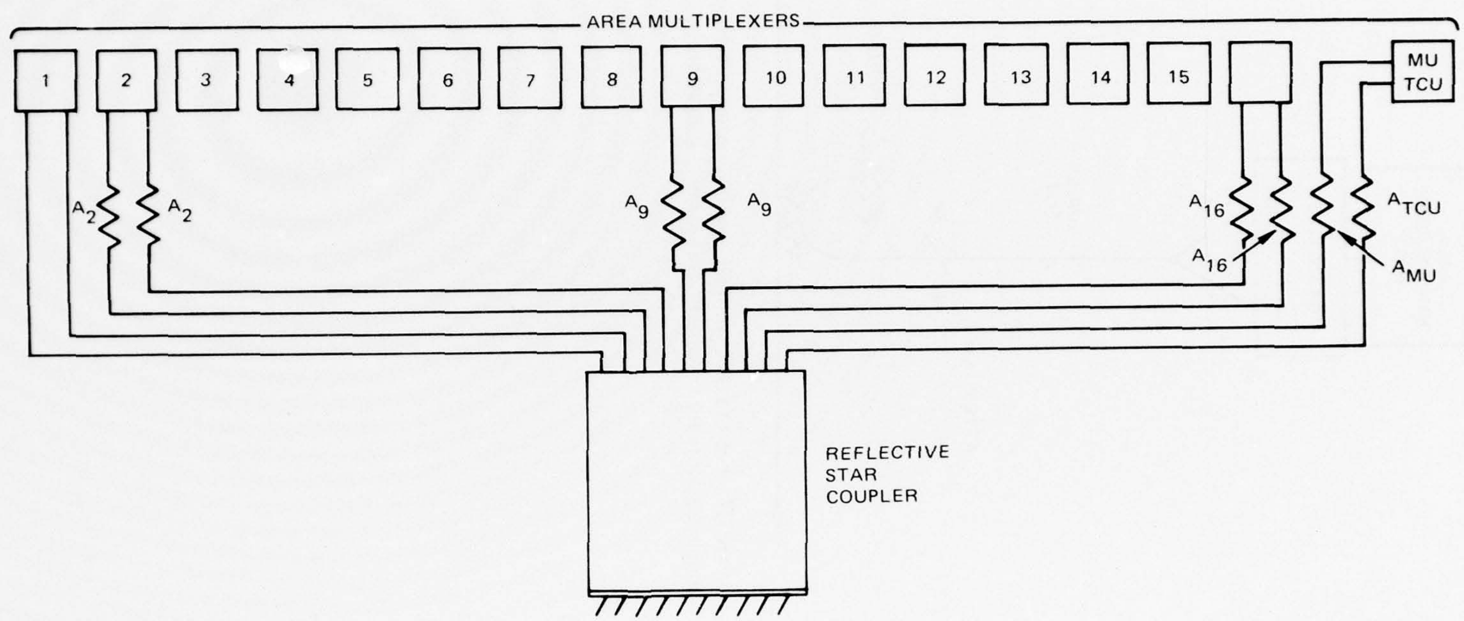

Figure C8. Equalization of star coupler.

APPENDIX D*
RECENT SINGLE-FIBER COUPLER DEVELOPMENTS

During final editing of this report, the following significant single-fiber coupler developments were reported.

Dabby and Chesler[D1] report the development of single-fiber couplers somewhat similar to those proposed in appendix A. In this development, however, coupling is accomplished by fusing the cladding so that the cores may be brought into close proximity for a portion of their length. The required fusion was done using a jeweler's torch, and was said to be possible without altering the cores because of the relatively lower melting point of the cladding. According to the measurements reported, the coupling factors range from −12.5 dB down to −42 dB, which is too low to meet the −9 dB requirements of a 17-tap bus such as the nominal size SDMS. Of the two couplers having −12.3 dB coupling factors suitable for a 34-tap bus, such as the maximum size SDMS, one has an excess loss of 4.04 dB; the other, 11.5 dB. For comparison, this study estimated the requirement as 0.6 dB, including the losses of two connectors.

A similar coupler is reported by Barnoski and Friedrich,[D2] on which controlled fusion of the cladding was accomplished by a CO_2 laser beam. The published excess loss of 1.1 dB and a coupling factor of −11.8 dB are improvements over the foregoing, but still fall short of meeting the requirements of SDMS.

Even though these early results do fall short of the requirements of SDMS, they show promise, given sufficient development effort.

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*Note added in publication

[D1] Fiber Communications Inc, Contract/Purchase Order No N00953-76-M-A283, Report on the Fabrication and Testing of a Four Port Single Fiber Coupler, by R Chesler and F Dabby, 8 November 1976

[D2] Barnoski, MK and Friedrich, HR, Fabrication of an Access Coupler with Single-Strand Multimode Fiber Waveguides, Applied Optics/vol 15, no 11, November 1976

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